AFWAL-TR-85-2060

VOLUME III - On-Board Inert Gas Generator System (OBIGGS) Studies
PART 1 - OBIGGS Ground Performance Tests

VULNERABILITY METHODOLOGY AND PROTECTIVE MEASURES FOR AIRCRAFT FIRE AND EXPLOSION HAZARDS

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AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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R. G. Clodfelter, Chief
Fire Protection Branch
Fuels and Lubrication Division
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FOR THE COMMANDER

R. D. SHERRILL
Chief, Fuels and Lubrication Division
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Results of performance evaluation tests of a molecular sieve (MSIGG) and a permeable membrane inert gas generator (PMIGG) system for airplane fuel tank inerting are presented. The IGG units, sized to inert the wing tanks of a KC-135, and the test facilities at Wright-Patterson Air Force Base are described. Steady state performance envelope, endurance, and KC-135 mission simulation tests are conducted. The weight and fuel penalties of the MSIGG and the PMIGG installed in a KC-135 are compared. Keywords: [illegible] Inert gas generator systems, NEA (Nitrogen Enriched Air), Fuel tank inerting, [illegible]

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11. TITLE

VULNERABILITY METHODOLOGY AND PROTECTIVE MEASURES FOR AIRCRAFT FIRE AND EXPLOSION HAZARDS

Volume III - On-Board Inert Gas Generator System (OBIGGS) Studies
Part 1 - OBIGGS Ground Performance Tests

This report is one of the set of aircraft fire protection reports contained in AFWAL-TR-85-2060 as listed below:

Volume I Executive Summary

Volume II Aircraft Engine Nacelle Fire Test Program

Part 1 Fire Detection, Fire Extinguishment and Hot Surface Ignition Studies

Part 2 Small Scale Testing of Dry Chemical Fire Extinguishants

Volume III On-Board Inert Gas Generator System (OBIGGS) Studies

Part 1 OBIGGS Ground Performance Tests

Part 2 Fuel Scrubbing and Oxygen Evolution Tests

Part 3 Aircraft OBIGGS Designs

PREFACE

Aircraft fire protection research conducted by the Boeing Military Airplane Company under Contract F33615-78-C-2063 is discussed in this report. Most of the research was carried out in newly activated facilities, the Aircraft Engine Nacelle (AEN) simulator, and the Simulated Aircraft Fuel Tank Environment (SAFTE) simulator located at Wright-Patterson Air Force Base and was conducted between February 1981 and October 1984. The contract was sponsored by the Air Force Wright Aeronautical Laboratories (AFWAL) and the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS). Guidance was provided by the Fire Protection Branch of the Aero Propulsion Laboratory (AFWAL/POSH), Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Project 3048, Task 07, and Work Unit 86. Gregory W. Gandee, Terrell D. Allen, and John C. Sparks were the Government project engineers.

The results are presented in three volumes with Volumes II and III subdivided into parts. Volume I summarizes the research conducted under this program, describes the test facilities used, and highlights important findings. Volume II discusses research related to engine compartment (nacelle) fire protection. Testing was done primarily in the AEN simulator, but some small scale testing was performed at Boeing facilities in Seattle. Volume III discusses fuel tank fire protection research studies performed under this contract. Most of this work was focused on on-board inert gas generator systems (OBIGGS). Much of the testing related to OBIGGS development was conducted in the SAFTE simulator, but again some related small scale testing was done in Seattle. The contents of the three volumes are listed below:

Volume I <u>Executive Summary</u>

Volume II <u>Aircraft Engine Nacelle Fire Test Program</u>

Part 1 Fire Protection, Fire Extinguishant and Hot Surface Ignition Studies

Part 2 Small Scale Testing of Dry Chemical Fire Extinguishants

Volume III On-Board Inert Gas Generator System (OBIGGS) Studies

Part 1 OBIGGS Ground Performance Tests

Part 2 Fuel Scrubbing and Oxygen Evolution Tests

Part 3 Aircraft OBIGGS Designs

Boeing acknowledges the contributions of the design and technical personnel of Technical/Scientific Services, Inc. (TSSI) for their support to this program and to R. G. Clodfelter of the Air Force for his technical guidance during the research studies and for his efforts to develop these National facilities for generalized investigations of techniques to improve aircraft fire safety.

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1.0 INTRODUCTION

Fire protection, a primary design consideration for military aircraft, has become increasingly important with the introduction of increasingly sophisticated and costly aircraft into the fleet. Since fuel fires are the most common and potentially the most severe, fuel tank fire safety is fundamental and is the object of extensive, continuing research.

Fuel tank fire protection research has resulted in implementation of several protection systems. Explosion suppressant foam, used in the fuel tanks of a number of fighter aircraft, causes in-tank fires to become extinguished before damaging overpressures occur. Although explosion suppressant foam provides effective explosion protection and is a passive (no moving parts) system, foam is relatively heavy and may be subject to electrostatic problems or premature decomposition. Liquid nitrogen (LN_2) fire protection systems are used on the Air Force C-5 fleet. The LN_2 system provides fuel tank fire protection by supplying sufficient nitrogen from storage bottles (dewars) to maintain an inert fuel tank vapor space (ullage). The consensus of extensive research is that the ullage will be inert (will not propagate flame) if the oxygen concentration is less than 9% by volume. The LN_2 system provides effective fuel tank fire protection but has the disadvantage of requiring a supply of cryogenic nitrogen nearly every time the airplane is refueled - a serious logistics problem. Another fire protection technique is to inject Halon into the ullage when a hazardous condition (such as combat) can be anticipated. Although Halon is a very effective fire protection agent, Halon is only suitable for part-time fuel tank fire protection and has logistics disadvantages. An attractive alternative to these methods is the on-board inert gas generator systems (OBIGGS) currently under development. The OBIGGS is similar to the LN_2 system except the OBIGGS produces an inert gas by processing engine bleed air into a nitrogen rich gas suitable for inerting. The OBIGGS eliminates the logistics problems of resupply for the LN_2 and Halon systems and has significant weight advantages over explosion suppressant foam.

1.1 Background

From as early as the 1960's, the Air Force has been interested in an on-board system which could generate inert gas for fuel tank inerting and fire suppression. The technology initially considered for this application included:

- o Permeable Membranes
- o Molecular Sieves
- o Catalytic Reactors

In 1978, the Air Force contracted with AiResearch (Contract F33615-77-C-2023) to design, build and flight test a fuel tank inerting system based on an on-board inert gas generator. The results of this program are reported in Reference 1. The inerting system developed by AiResearch was to be flight tested on a KC-135 airplane. Subsequently, the Air Force cancelled the flight test portion of the AiResearch contract and substituted an in-depth ground test program under a separate contract with Boeing Military Airplane Company (F33615-78-C-2063). AiResearch was still under contract to provide the IGG as a skid system, including the bleed air conditioning system referred to as an Air Cycle Machine (ACM). Later funding cuts on the AiResearch contract also resulted in the elimination of the ACM from the Inert Gas Generator (IGG) hardware delivered for ground testing.

AiResearch performed an analysis of the KC-135 inerting requirements and determined the following specifications for the IGG product flowrate and oxygen concentration:

- o 3 PPM at 5 % O_2
- o 8 PPM at 9 % O_2

The AiResearch IGG was based on a hollow fiber permeable membrane concept under development by DOW Chemical Company. An inerting system, capable of meeting the KC-135 requirements, was initially designed on the basis of projected performance from five 13-inch diameter ASM's. However, initial attempts by DOW to produce a 13-inch diameter ASM were not completely successful.

DOW eventually produced 9-inch diameter ASM's, and AiResearch delivered a skid based PMIGG consisting of five 9-inch ASM's rated at one-half of the KC-135 requirements (1.5 PPM at 5 % O_2 and 4 PPM at 9 % O_2).

In 1980, the Air Force contracted with the Instruments & Life Support Division of the Clifton Precision Company (Contract F33615-80-C-2007) to produce an alternative IGG. This program is described in Reference 2. The Clifton unit uses molecular sieves to generate the inert gas. Clifton had previous experience using the molecular sieve process to produce systems similar in operation to an IGG for breathing oxygen. However, the MSIGG unit provided by Clifton was significantly larger in flow rate than any similar system previously produced. The specifications for the MSIGG were provided by the Air Force and were based on the AiResearch analysis of the KC-135 inerting requirements. The Clifton MSIGG, as delivered, met the 3 and 8 PPM requirements mentioned previously and underwent the same extensive ground tests as the AiResearch PMIGG.

1.2 Ground Rules

The basic requirements for this study were to install, checkout, and conduct a comprehensive performance evaluation of two prototype OBIGGS: one used the molecular sieve concept for inert gas production while the other used the permeable membrane concept. The performance evaluation required ground simulation of selected, critical flight environments and related operating conditions. The performance goals of both concepts were to provide flowrates and nitrogen enriched air with specified oxygen concentrations for various mission segments as tabulated below:

Mission Segment	NEA Flowrate (pounds per minute)	NEA Maximum Oxygen Concentration (% by volume)
Climb	3	5
Cruise	3	5
Descent	8	9

Each of the IGG devices was required to accumulate the equivalent of 200 flight hours based on fuel system demands for typical flight profiles of KC-135 airplanes. Particular attention was to be given to any performance degradation observed during testing.

During the ground simulation of the KC-135 missions, the performance requirements for both IGG's were as follows:

- o Fuel system pressure must remain positive (above simulated ambient) at all times to prevent ambient air from entering the fuel system.

- o The IGG product gas oxygen concentration must remain below 9% O_2 at all times.

- o The fuel system ullage oxygen concentration should be reduced below 9% O_2 as soon as possible and maintained below 9% thereafter.

1.3 Report Organization

Performance data were obtained on a Clifton molecular sieve unit and an AiResearch permeable membrane unit; each OBIGGS was then compared with each other and with other fuel tank fire protection concepts. The units tested are described in Section 2. The facility used to obtain the performance data, including instrumentation and data acquisition characteristics, is discussed in Section 3. Performance of the units for both steady state operation and simulated missions was of interest; the test procedures followed to acquire this information are outlined in Section 4. An extensive amount of performance data were obtained. As the tests proceeded, changes in performance and unit malfunctions, as well as basic performance data were important results from the test program. These results are summarized in Section 5. The comparison between units is given in Section 6. Finally, conclusions and recommendations are presented in Section 7.

2.0 DESCRIPTION OF PMIGG AND MSIGG UNITS

The focus of this study was the performance of molecular sieve inert gas generator (MSIGG) and permeable membrane inert gas generator (PMIGG) units. Accordingly, a brief description of the units is provided below, discussing their methods of operation, similarities, and differences.

2.1 Permeable Membrane Unit

The permeable membrane reduces the oxygen content of air by imposing a relatively high differential pressure across an array of hollow fiber membranes. The unit tested in this program had the high pressure conditioned air applied to the outside of the hollow fibers (externally pressurized), while the insides of the fibers were vented to ambient pressure. The process is illustrated for a single hollow fiber in Figure 1. As air flows around the hollow fiber, both nitrogen and oxygen molecules migrate through the fiber wall, but at different rates. Since the membrane material is more permeable to oxygen, the gas on the fiber exterior becomes progressively richer in nitrogen, while the gas inside the fiber becomes oxygen enriched. An actual separation unit has many hollow fibers manifolded together (4 million per module) to achieve the required oxygen concentration and flow rate of the product (inert) gas. A diagram of a complete permeable membrane air separation module (ASM) is shown in Figure 2. The fiber bundle is 8.5 inches in diameter, and the overall diameter is 10 inches including the pressure case.

A schematic and photograph of the PMIGG unit, as tested, are shown in Figures 3 and 4. The PMIGG unit consisted of five ASM's manifolded in parallel with each ASM containing an 8.5-inch diameter fiber bundle. This particular unit is rated at approximately one-half the capacity required for a KC-135, as discussed in Section 1.1. A full size unit would require 10 8.5-inch dia. ASM's or five 13-inch dia. ASM's as originally planned.

Referring to Figure 3, the inlet air (simulated air cycle machine outlet) first flows through a water extractor which is required to remove liquid water under certain high dew point conditions. Next is a particulate filter to prevent clogging of the ASM's, followed by a dual pressure regulator. The dual pressure regulator operates at two different pressure settings for both high and low flow modes and is actually a PSID regulator referenced to waste

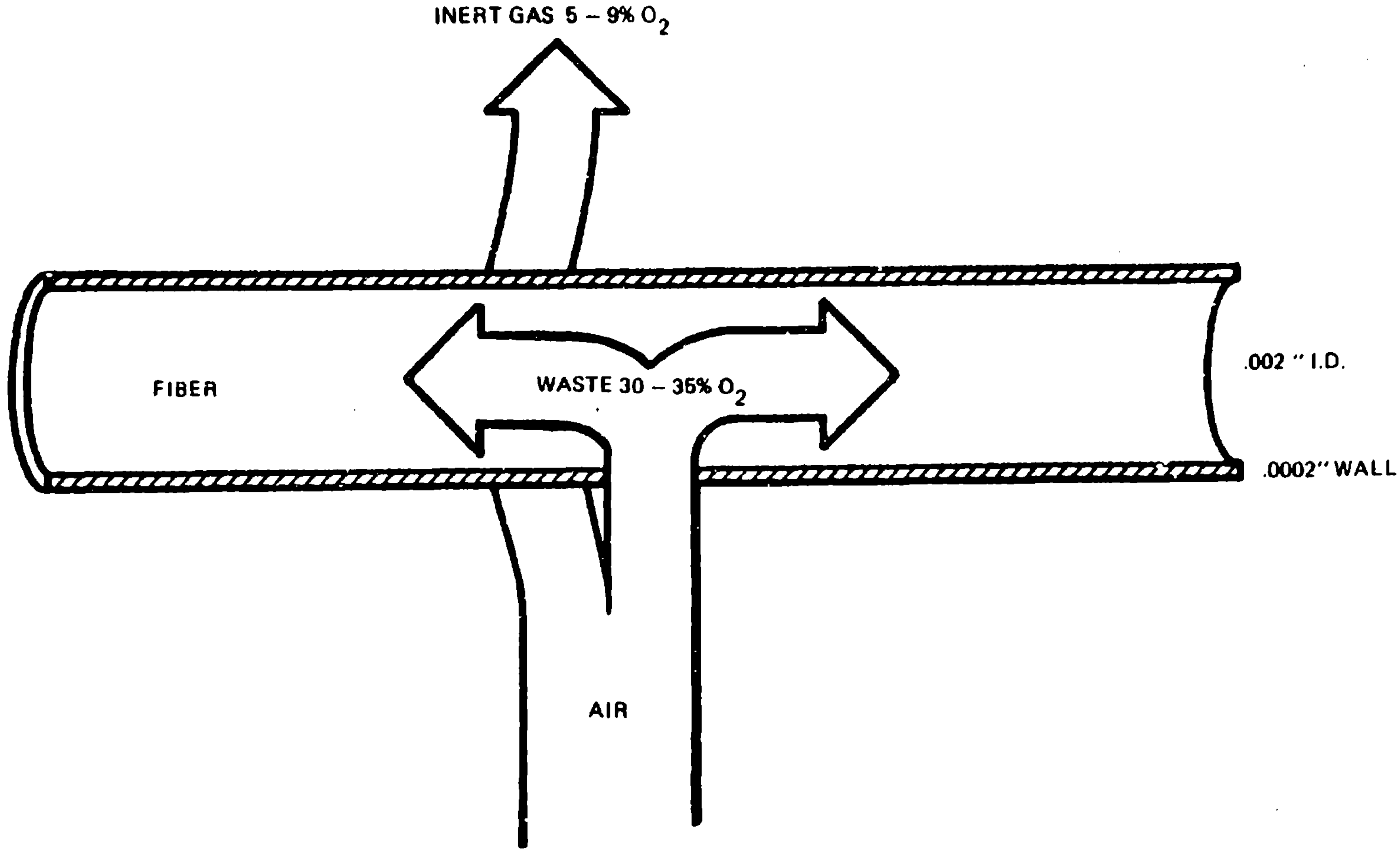
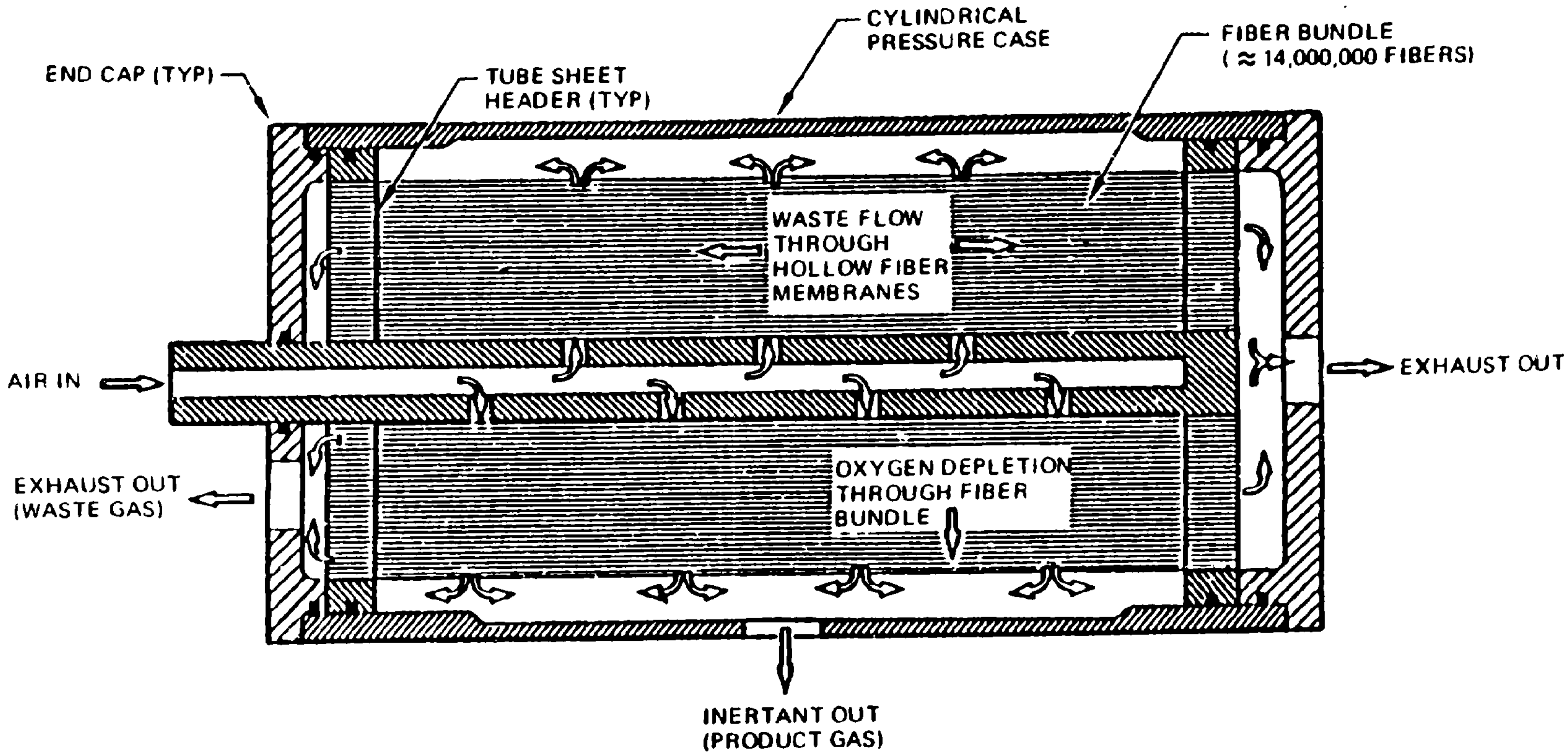


Figure 1. Single Fiber PMIGG Example



Note:

APPROXIMATE MODULE DIMENSIONS:
10 IN OD, L ≈ 46 IN

Figure 2. PMIGG Air Separation Module Cross Section

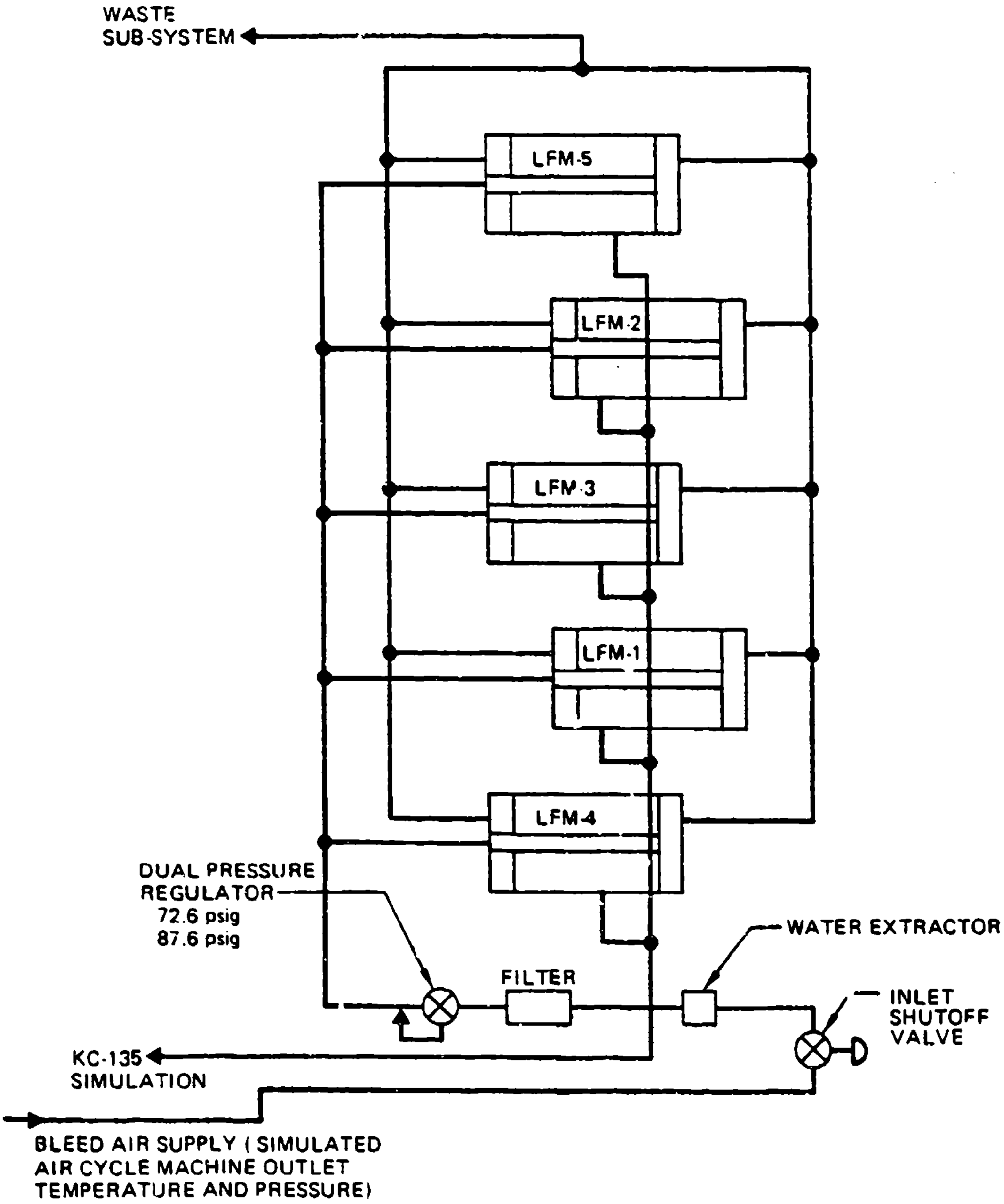


Figure 3. Schematic of a 5 Module PMIGG

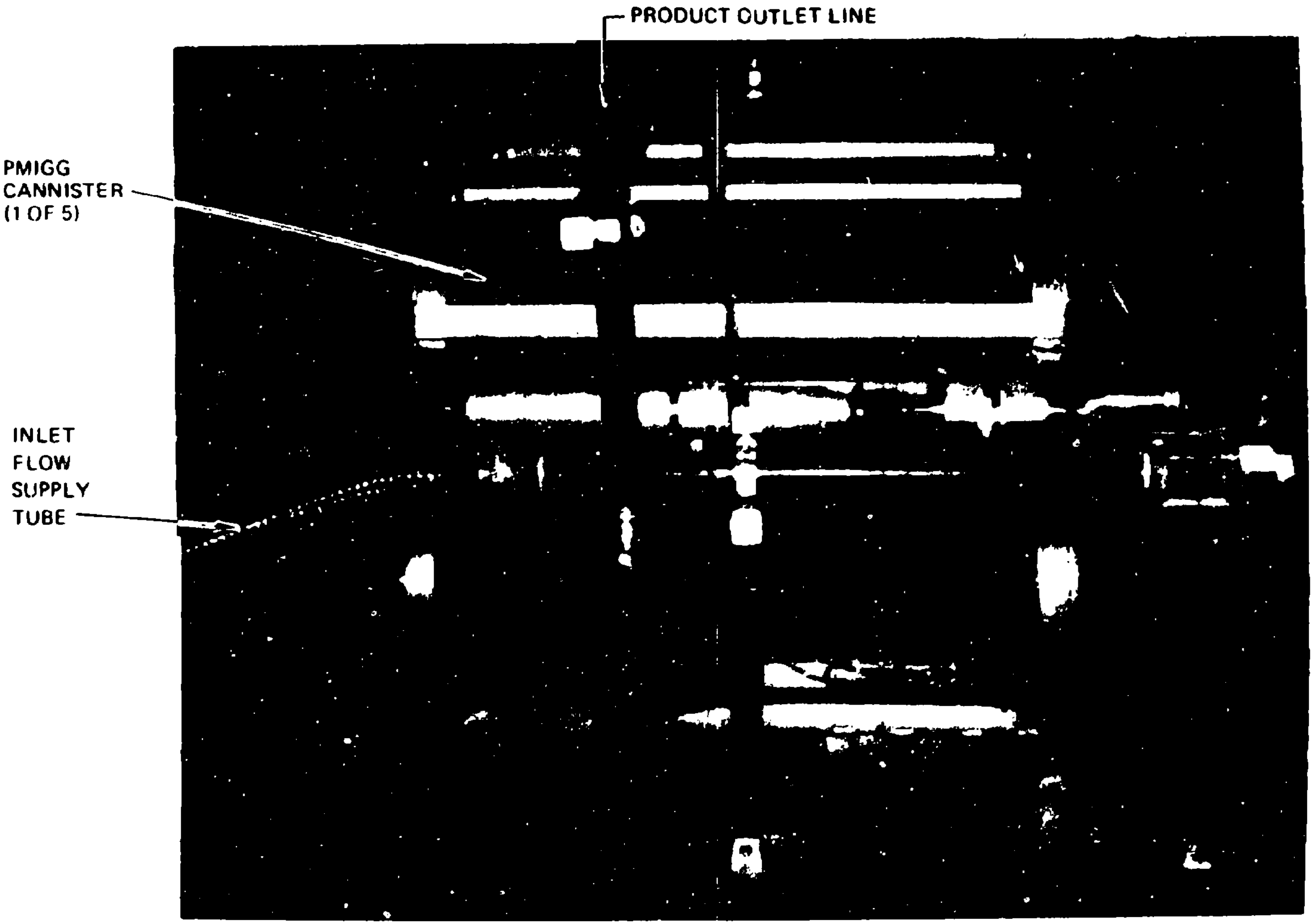


Figure 4. Photograph of 5 Module PMIGG

pressure. Consequently, the regulator controls the differential pressure across the fiber bundle.

Thermal insulation was added to the unit to minimize heat transfer when testing at temperatures above or below ambient.

2.2 Molecular Sieve Unit

An MSIGG consists of two or more canisters filled with a zeolite material (these canisters are termed "beds"); the zeolite preferentially adsorbs oxygen from high pressure air. Consider for simplicity a two bed MSIGG (Figure 5). Air flows through the first bed where the zeolite adsorbs oxygen from the air and nitrogen rich gas is produced. Since the zeolite has limited capacity, when the limit of oxygen adsorption is reached, the second bed is activated allowing the first to be purged of adsorbed oxygen. The beds are alternatively on and off line; the off-line unit is purged by pressure reduction and by a small wash flow of nitrogen enriched air produced by the on-line unit. In application, more than two modules can be used by providing properly sequenced inlet and exhaust valves.

A schematic and photograph of the MSIGG unit, as tested, are shown in Figures 6 and 7. The MSIGG unit consisted of eight beds of sieve material manifolded in parallel with each bed containing 50 pounds of sieve.

Referring to Figure 6, the inlet air first passes through a coalescer filter to remove particulates and extract liquid water from saturated inlet air. The air next flows through a differential pressure regulator which is referenced to waste pressure thereby controlling the difference between inlet and exhaust pressure (i.e. pressure swing). The regulator setting is controlled by a digital control system (part of the MSIGG unit). This digital control system provides for six different pressure settings as a function of altitude, bed temperature, and descent switch setting (Table 1). The regulated inlet air then enters each of the eight beds through inlet valves. Each bed is alternately pressurized with inlet air and then exhausted to the waste subsystem in a staggered timing arrangement (see Appendix B) controlled by the digital control system. Whenever a bed is pressurized, NEA flows through a check valve to the product manifold which collects product gas from all eight

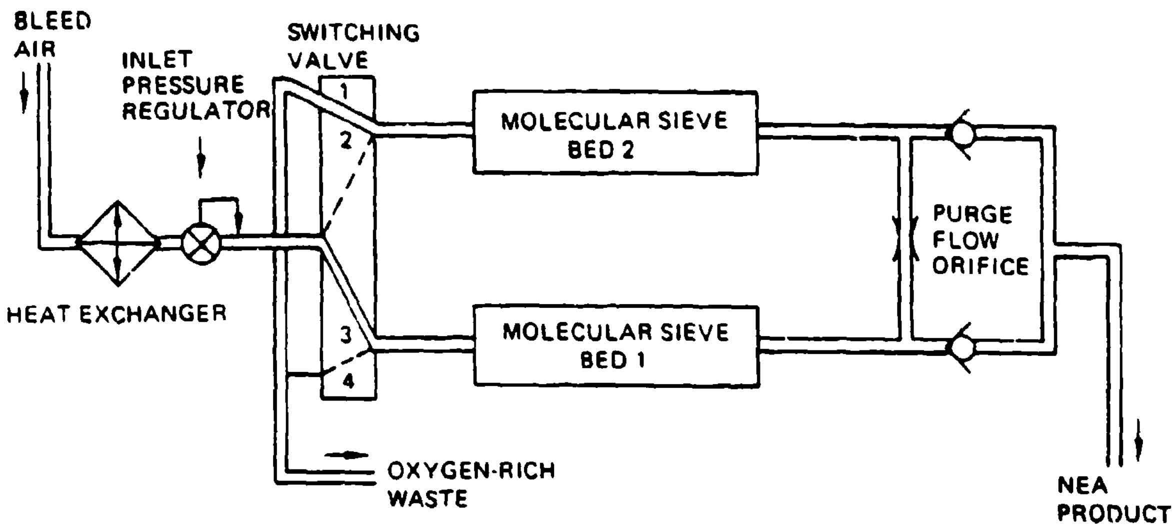


Figure 5. Simplified 2 - Bed MSIGG Example

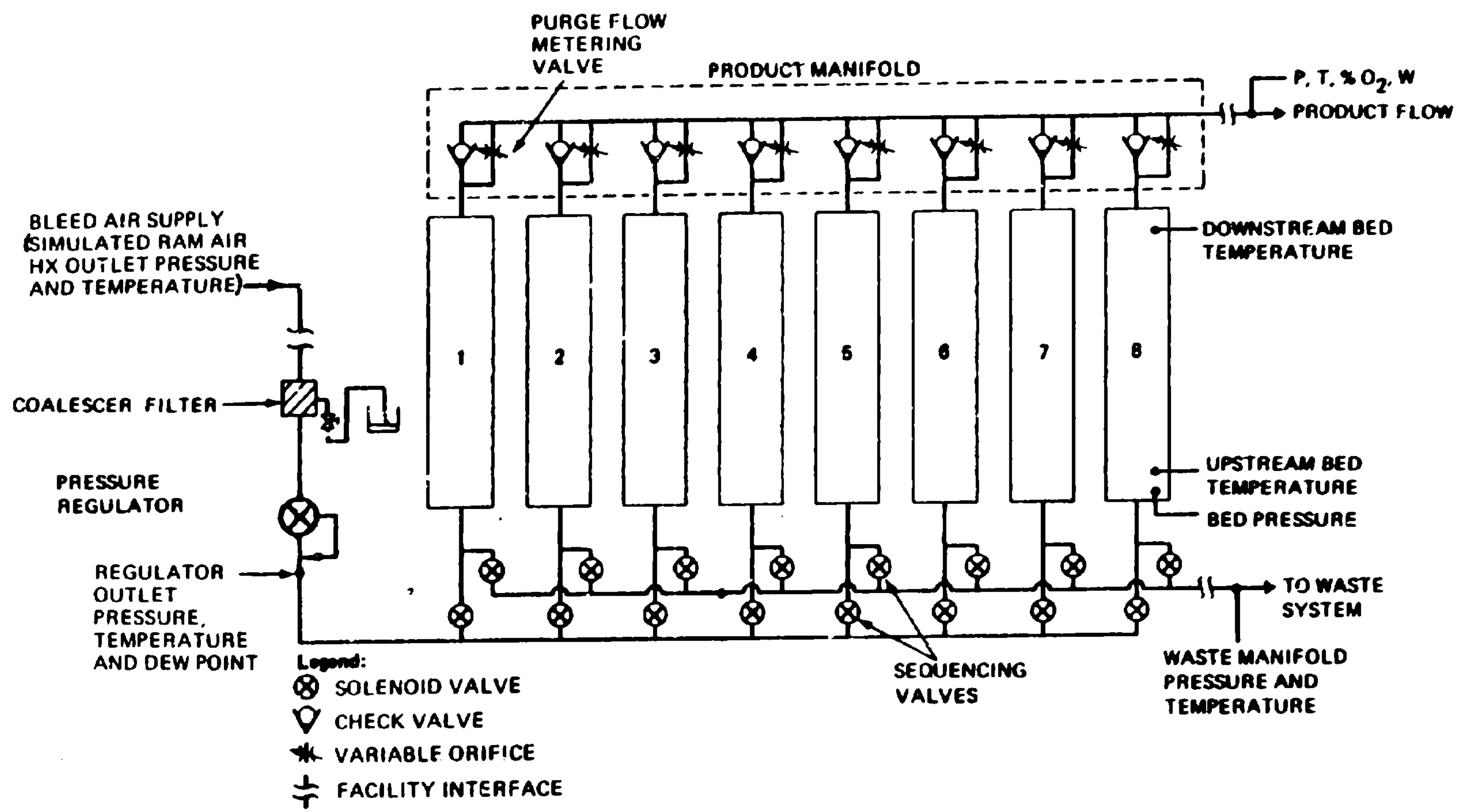


Figure 6. Schematic of an 8 - Bed MSIGG

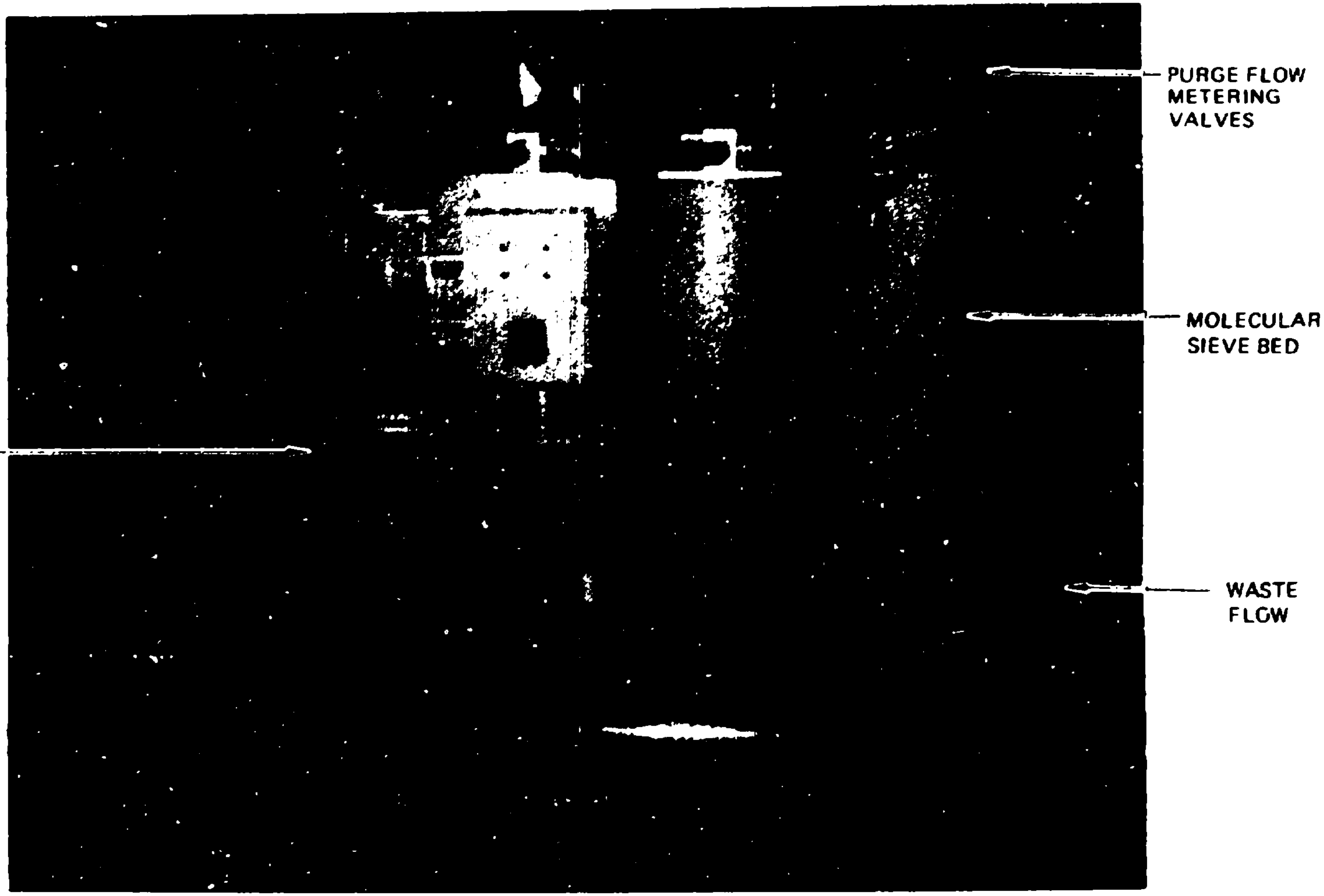


Figure 7. Photograph of 8 Bed MSIGG

Table 1. MSIGG Regulator Schedule

REGULATOR PRESSURE SETTINGS (PSIG)		
Bed Temp	Altitude	
	< 30,000 ft	> 30,000 ft
> 54°F	43.0*/43.0*	23.0/43.0*
30° - 54°F	25.9/43.0*	19.5/23.5
< 30°F	23.4/43.0*	18.5/22.6

3 PPM/8 PPM

* Changed from the manufacturer's original setting of 35.5 PSIG

beds. During the exhaust part of the cycle, the check valve prevents reverse flow of NEA into the beds with an exception of a small quantity of NEA purge flow through a metering valve (0.75 CFM per bed). This metered backflow is designed to aid in purging oxygen from the sieve material. The product gas pressure is controlled by a regulator to provide constant outlet pressures to the simulated KC-135 fuel system.

2.3 Airplane Installation

Both of the IGG units were originally designed and sized by the respective manufacturers to satisfy the inerting requirements of the wing tanks of a KC-135 airplane. However, the PMIGG was actually delivered as a half size unit, as discussed in Section 1.1. The IGG units were continuous flow units which operated in either one of two modes. The low flow mode produced a gas which contained about 5% oxygen and was used for scrubbing dissolved oxygen from the fuel during climb and for tank pressurization due to fuel depletion during the cruise portion of the flight. The high flow mode produced a product gas which contained about 9% oxygen and was used for fuel tank repressurization during descent.

The installation of an OBIGGS on a KC-135 is depicted in Figure 8. More detailed information regarding the installation of the PMIGG in a KC-135 is provided in Reference 3. The PMIGG and MSIGG units installed in a KC-135 would have several common features. Both would use ram air to cool the high pressure, high temperature engine bleed air supply. The flow rates for the low flow and high flow modes would be essentially the same for both units. Both systems would use valves to control fuel tank pressures. Excess positive pressure would be vented overboard through a "climb" valve, while the "dive" valve would permit ambient air to enter the fuel tank to prevent tank collapse if the IGG unit did not maintain positive tank pressures.

The primary installation differences between the PMIGG and MSIGG on the KC-135 airplane (as designed by AiResearch and Clifton) was that the PMIGG would require an air cycle machine as well as ram air to adequately condition bleed air to the desired temperatures and pressures. The MSIGG would require only ram air cooling of the bleed air, since it could operate at lower pressures and higher temperatures than the PMIGG. However, the MSIGG would require sequencing valves and timers.

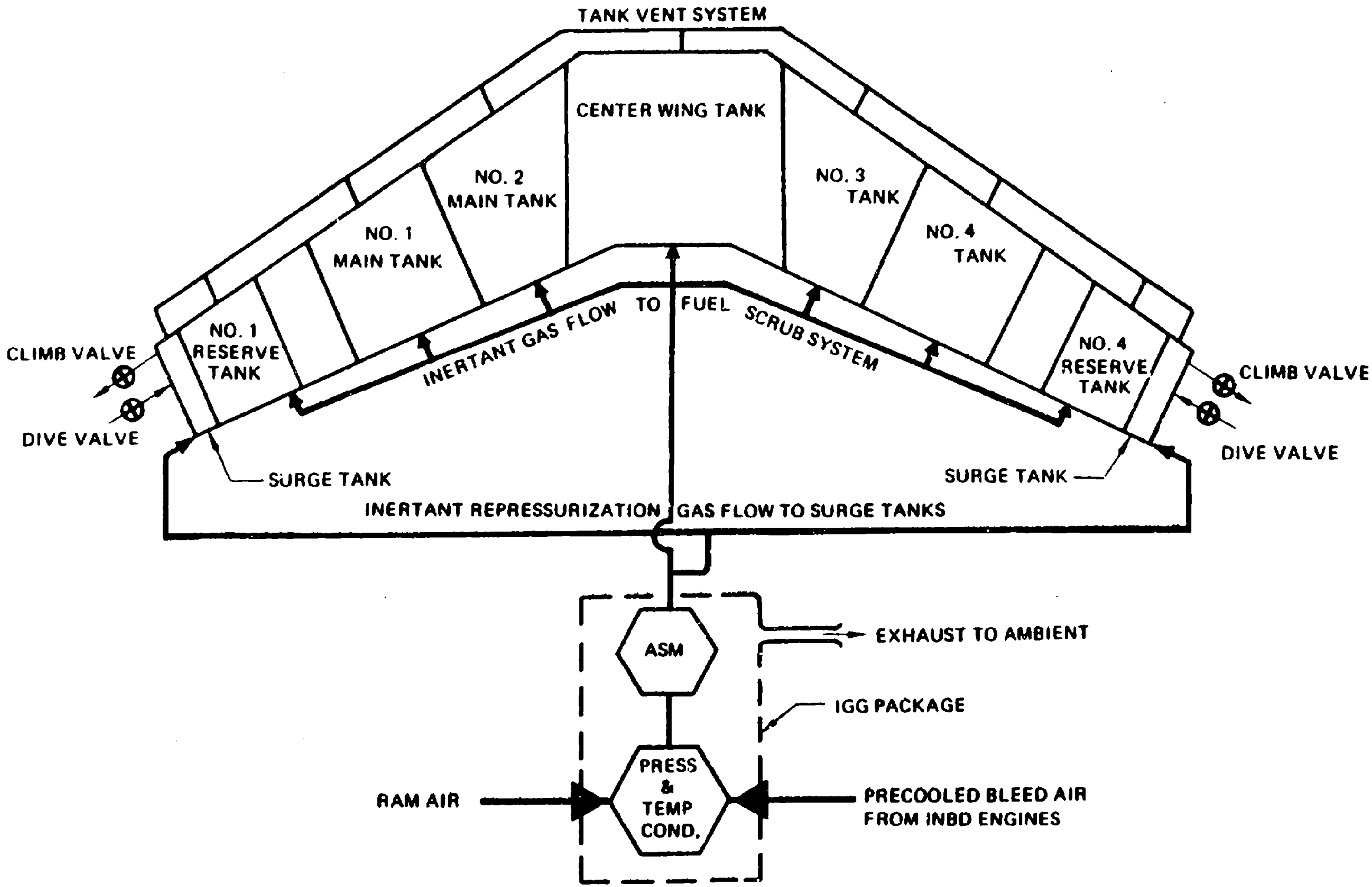


Figure 8. Fuel Tank Inerting System for the KC–135

As these OBIGGS were designed, the KC-135 would not receive true full time inerting. During airplane refueling, air saturated fuel would enter the fuel tanks and the evolution of dissolved oxygen could be expected to increase the ullage oxygen concentration above 9%. The OBIGGS were not designed to operate while the airplane is on the ground. Thus, the ullage would be non-inert until sometime after takeoff and until the scrub system actively reduced the ullage oxygen concentration.

3.0 TEST FACILITY

The two OBIGGS were evaluated in the USAF Simulated Fuel Tank Environment (SAFTE) simulator at Wright-Patterson AFB, Ohio. Existing USAF ground test facilities were modified to permit simulation of typical KC-135 flight profiles by proper time variation of:

- bleed air temperatures and pressures;
- exhaust (ambient) pressure; and
- KC-135 fuel system inert gas demand.

This simulation concept is depicted in Figure 9. The SAFTE facility consists of a rectangular tank with a fuel capacity of 582 gallons, and associated instrumentation and controls. The tank skin temperatures and fuel withdrawal rate were computer controlled to simulate a pre-selected flight. The tank was mounted on a platform which provided slosh and vibration simulation. Five gas sampling probes, which traveled vertically within the tank ullage, provided three dimensional mapping of the ullage composition. The gas samples collected were routed to a mass spectrometer for continuous on-line analysis. A vacuum system was used to simulate in-flight pressure. Standard pressure, temperature and flowrate instrumentation were provided, and the data were computer recorded.

3.1 Bleed Air and Waste Subsystems

Other elements of the modified ground test facilities were the bleed air and waste subsystems. The bleed air subsystem is depicted in Figure 10. This system used a 2000 psig compressor to charge a bottle farm with a storage capacity of 8800 pounds. During testing, air from the bottle farm provided the simulated bleed air pressure. The air was controlled by a throttle valve and a closed loop pressure controller. The bleed air flowrate was measured with a sonic nozzle. The bleed air temperature was controlled by an air/glycol heat exchanger for cooling and an electric heater for heating. Although the air was quite dry in the storage system, steam could be injected to simulate flights through high dew point air.

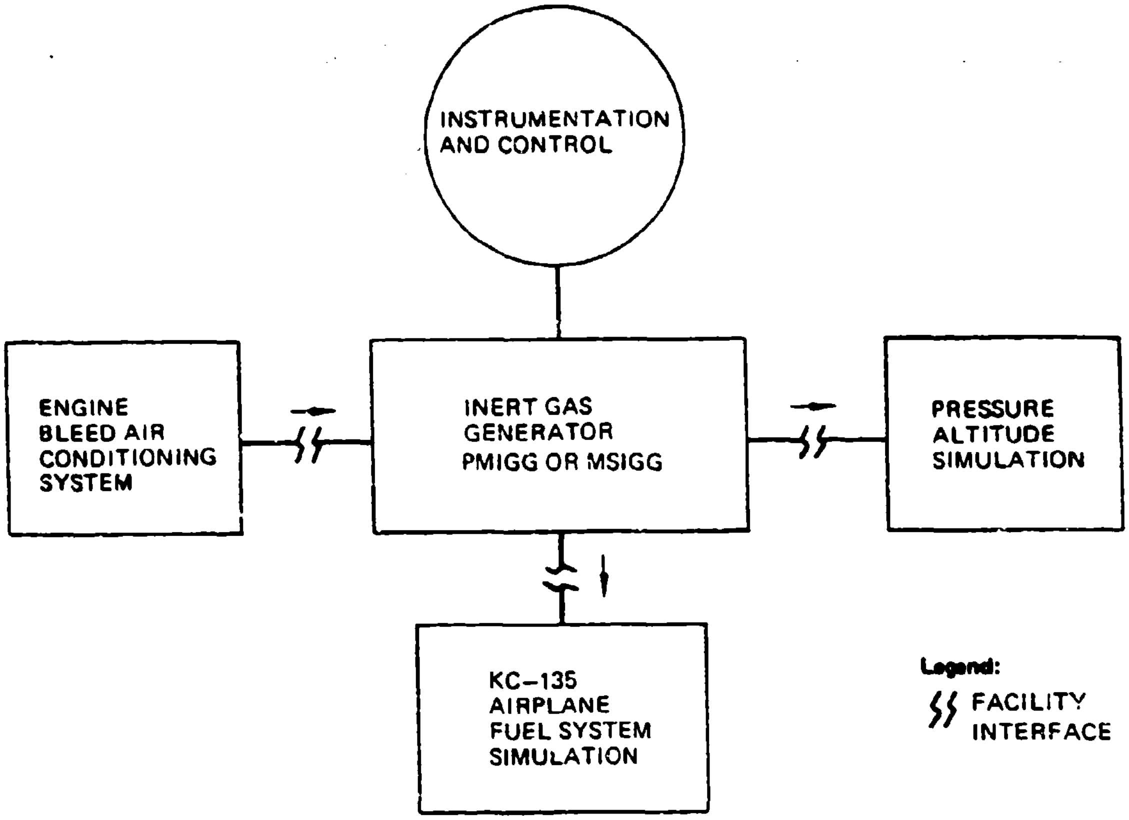


Figure 9. Block Diagram of KC–135 Simulation

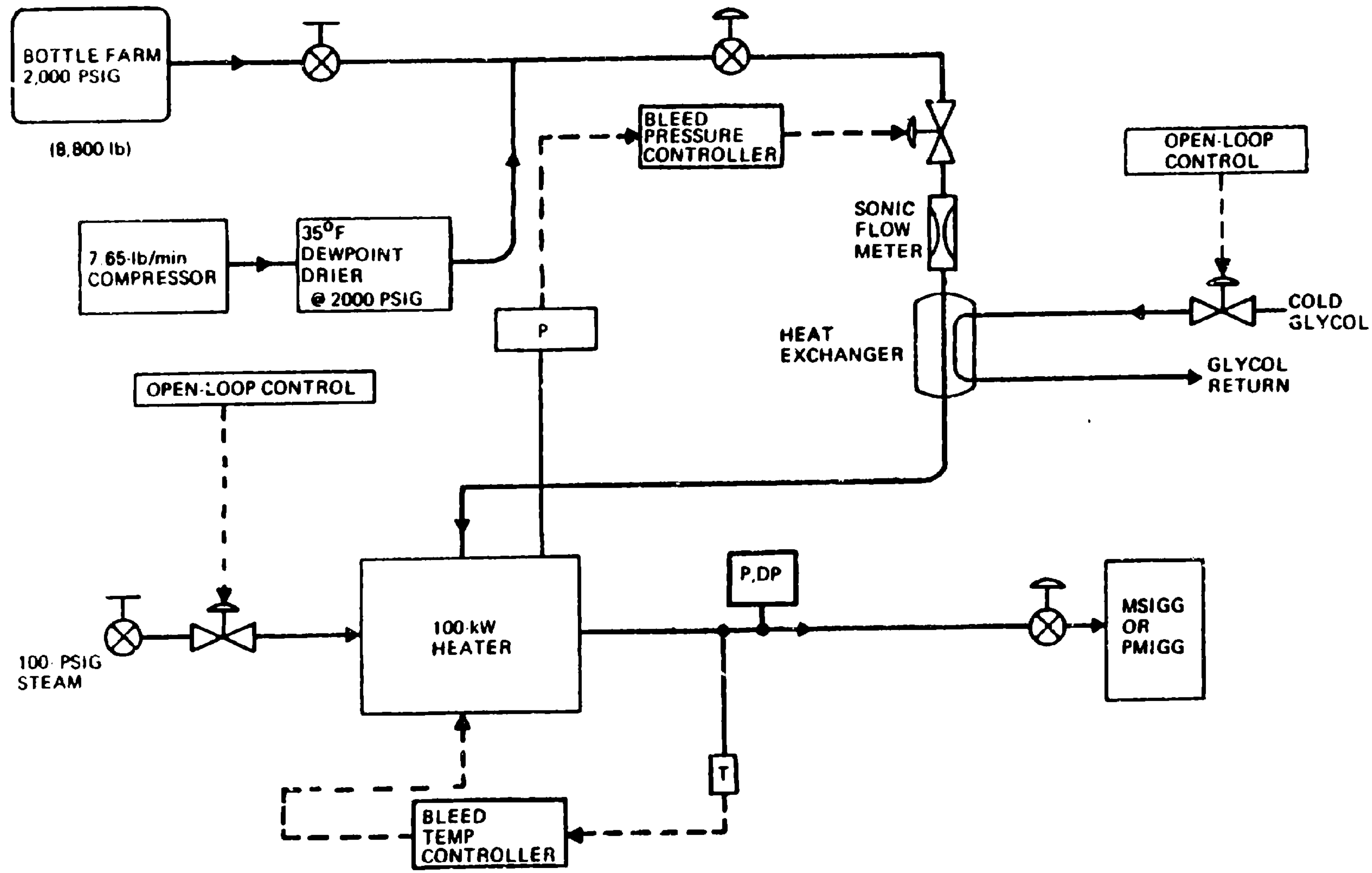


Figure 10. Bleed Air Subsystem Schematic

The waste subsystem is depicted in Figure 11 and maintained the back pressure for waste gas discharge at local ambient pressure in a simulated flight. Pressures from sea level to 46,000 feet were simulated by this system. The waste pressure was produced by two vacuum pumps and controlled by a throttle valve and a closed loop pressure controller. A 750-gallon reservoir dampened pressure pulsations from the MSIGG.

3.2 Flight Simulations

Flight simulations were computer controlled to automatically position valves and to set pressures and temperatures corresponding to in-flight boundary conditions on both the air separation modules and the airplane wing fuel tanks. These simulation control loops are depicted in Figure 12. Data acquisition, reduction, and presentation were handled by the same computer. Progress of the simulated mission was continuously monitored in the control room and provisions were made to revert to manual control if required.

3.3 Product Flow and KC-135 Fuel Tank Simulation

The basic philosophy behind the ground simulation of the IGG was to connect the IGG to the SAFTE system and measure oxygen concentrations in the fuel tank ullage space during a simulated mission profile. During this simulation, the fuel tank was pressurized with nitrogen enriched air (NEA) from the IGG. Since the SAFTE test tank volume was 582 gallons compared to 17,625 gallons for the KC-135 airplane (a 30.3:1 volume ratio), a flow proportioning scheme (Figure 13) was developed for the MSIGG in which 29.3 pounds of NEA was expelled to the atmosphere for each pound supplied to the SAFTE tank (29.3:1 flow split). The flow proportioning scheme used with the PMIGG was based on a 15.15:1 volume ratio since the PMIGG was a half size unit. For this scheme 14.15 pounds of NEA were expelled to the atmosphere for each pound supplied to the SAFTE tank (14.15:1 flow split).

The SAFTE tank, as configured to simulate a KC-135 fuel system, is shown in Figure 14. A C-5 scrub nozzle was installed in the tank and operated at fuel and NEA flowrates to match the KC-135 system design. The design flowrates for the KC-135 were in turn based on the scrub nozzle operation in the C-5 (Reference 4) as summarized below:

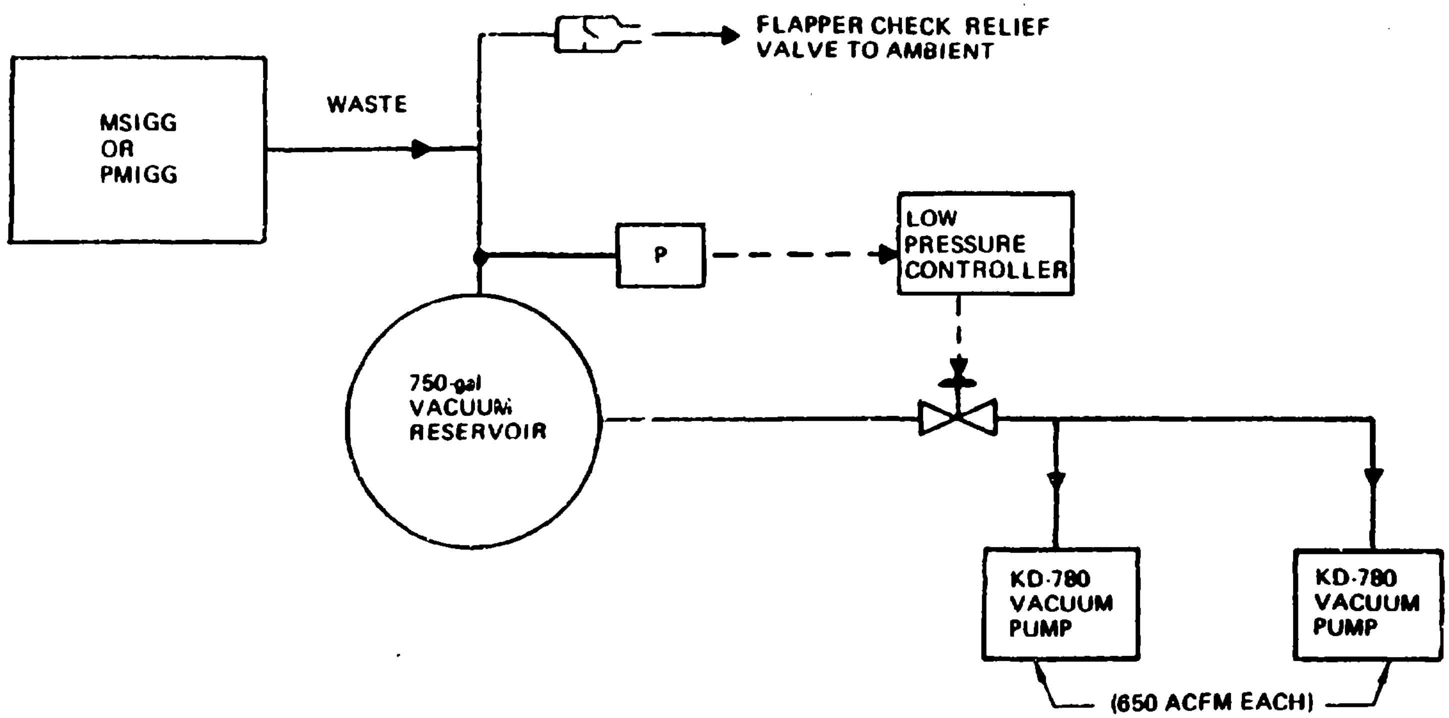


Figure 11. Waste Subsystem Schematic

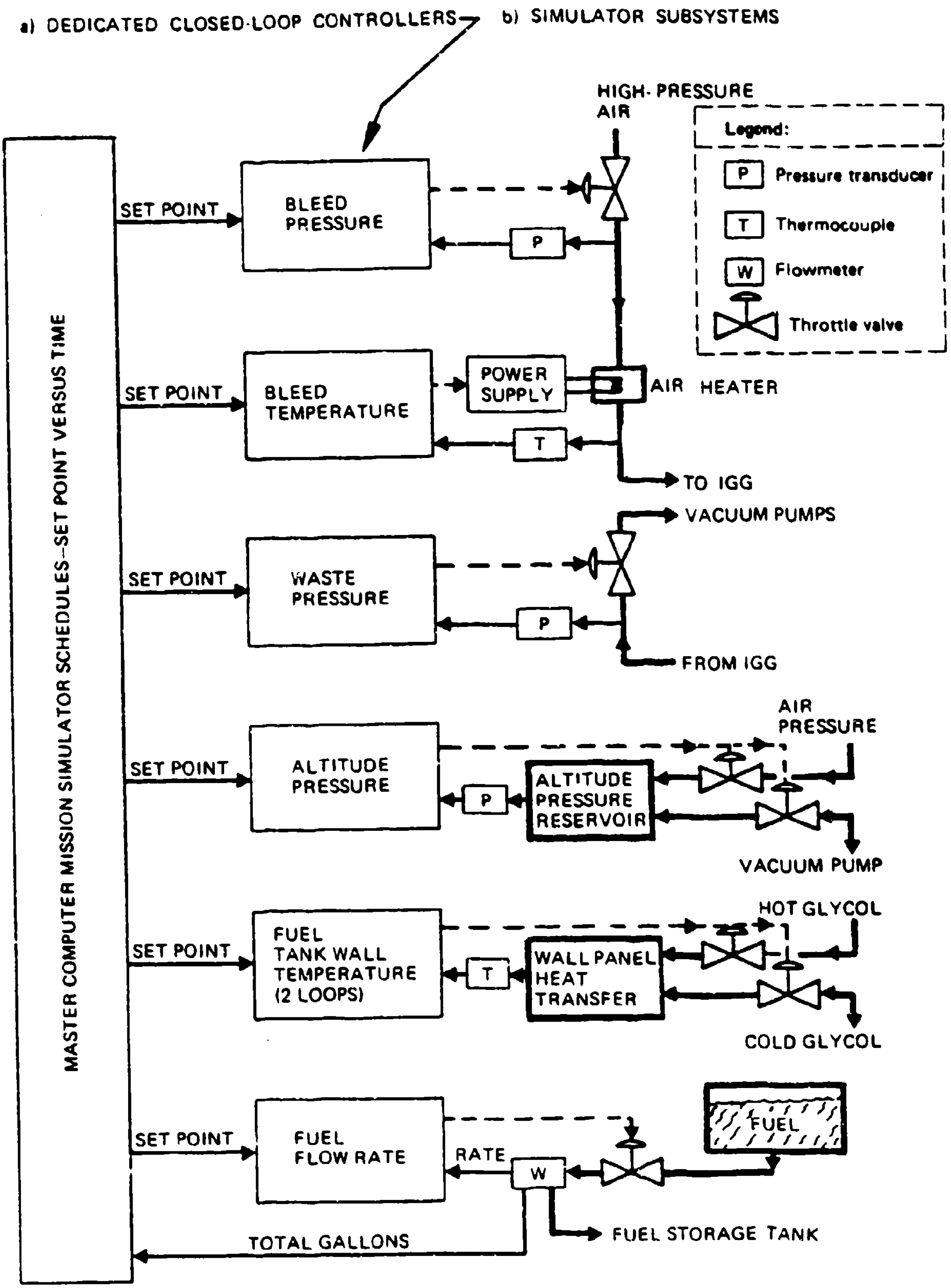


Figure 12. Simulation Control Loops

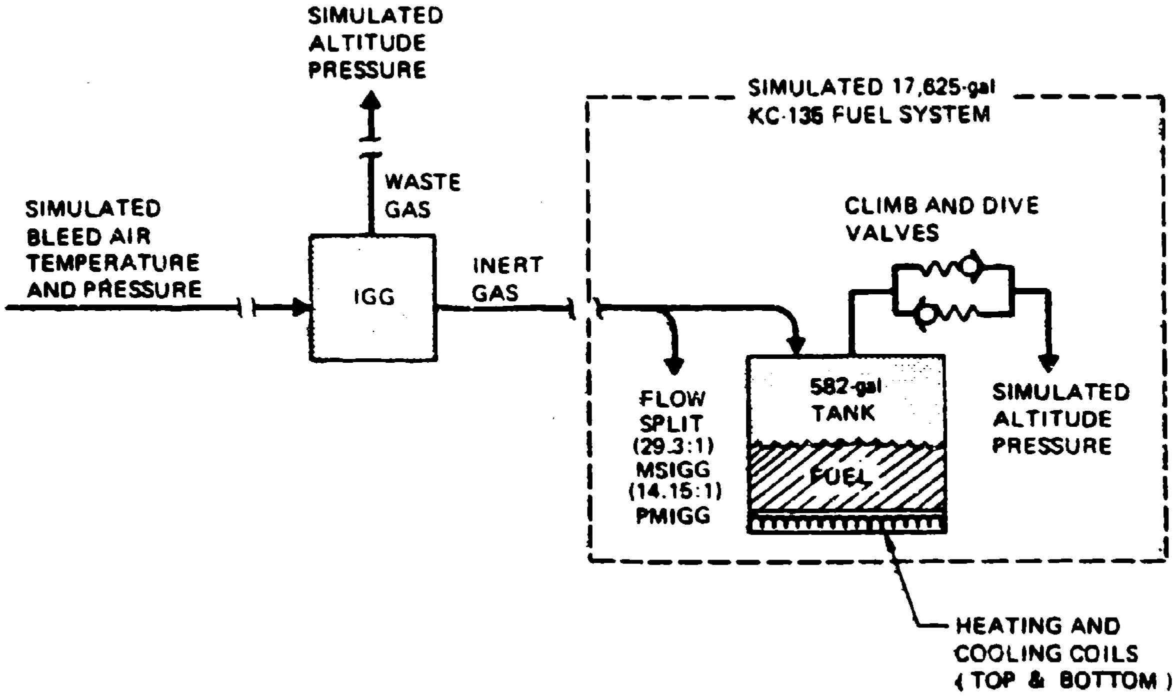


Figure 13. Flow Proportioning Scheme for KC—135 Simulation

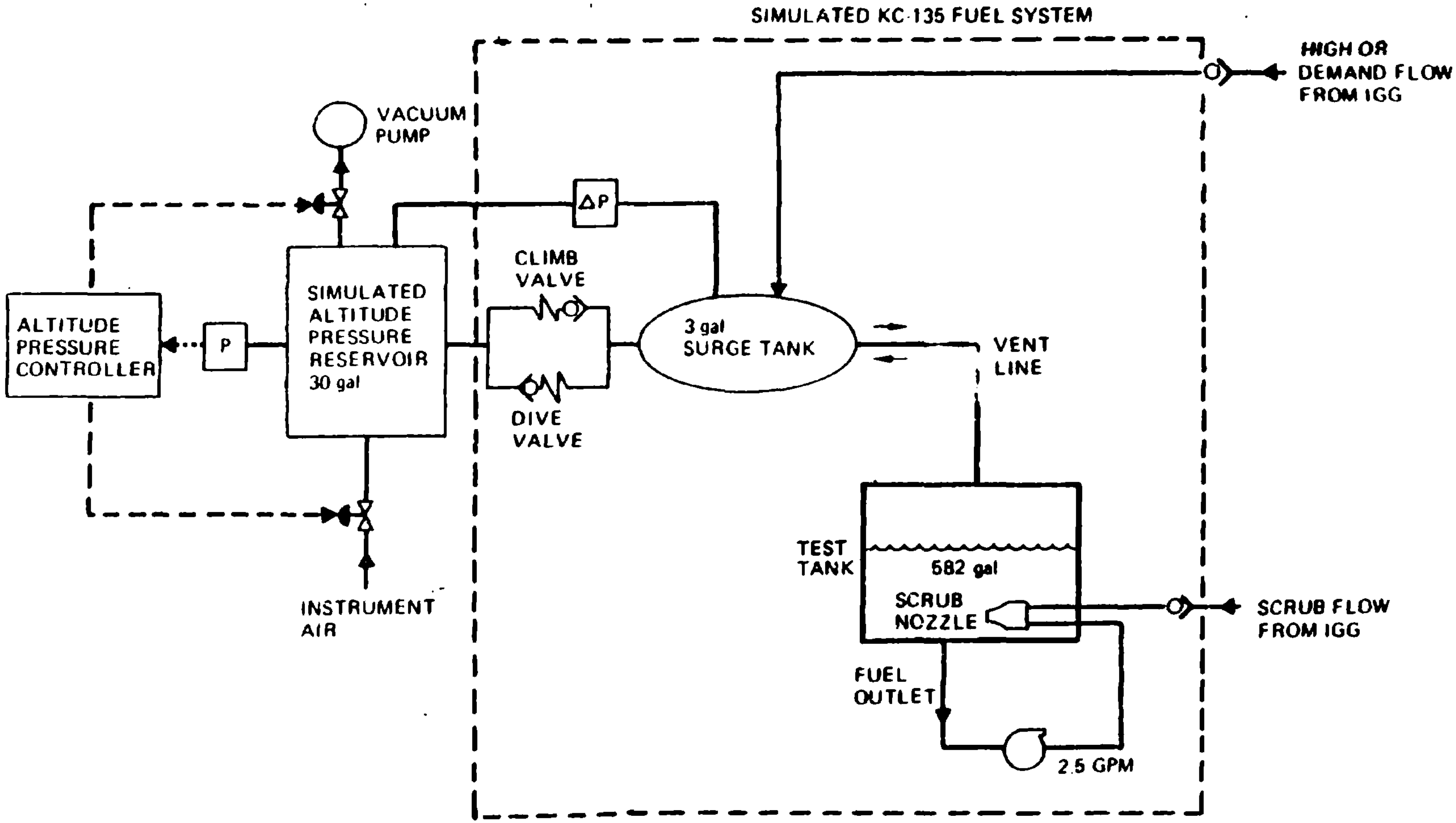


Figure 14. SAFTE Tank KC–135 Configuration

$\frac{1.6 \times 10^{-4} \text{ PPM NEA Scrub Flow}}{\text{Gallon of Tankage}}$

$\frac{\text{25 Gallons Fuel Thru Scrub Nozzle}}{\text{Pound of NEA Thru Scrub Nozzle}}$

Climb and dive valves were provided with the climb valve set to open at 2.3 psig. The tank was initially fueled with JP-4 which was at least 90% air saturated.

Each of the two IGG manufacturers had specified different fuel system pressure control schemes for the KC-135. This difference required separate test set-ups for proper mission simulations for each IGG system. These test set-ups are depicted in Figures 15 and 16 for the PMIGG and MSIGG.

3.4 Instrumentation

Primary instrumentation consisted of flow meters, pressure transducers, thermocouples, and gas analyzers. The data were recorded on a computer data system.

3.4.1 Measurement Devices

The total NEA (product) flow was measured by summing up to 6 individual flows (4 sonic nozzles and 2 laminar flow elements) and was recorded automatically by the computer data system. In general, a maximum of 2 flowmeters were used at any one time; during steady state performance tests, the laminar flow element for the demand excess flow was generally the only flowmeter used.

The product oxygen concentration was measured using a Beckman Model OM-11 medical oxygen gas analyzer. A small sample (500 ml/min or 0.001 PPM) was transported from the IGG product outlet connection to the OM-11 through 0.031" I.D. tubing, producing a response time better than 1 second. This fast response oxygen signal was of value when analyzing the MSIGG with varying oxygen concentrations.

A mass spectrometer analyzed continuously the ullage gas in the fuel tank simulator during mission simulations. Five separate samples of ullage gas were continuously transported in parallel from the fuel tank to the mass

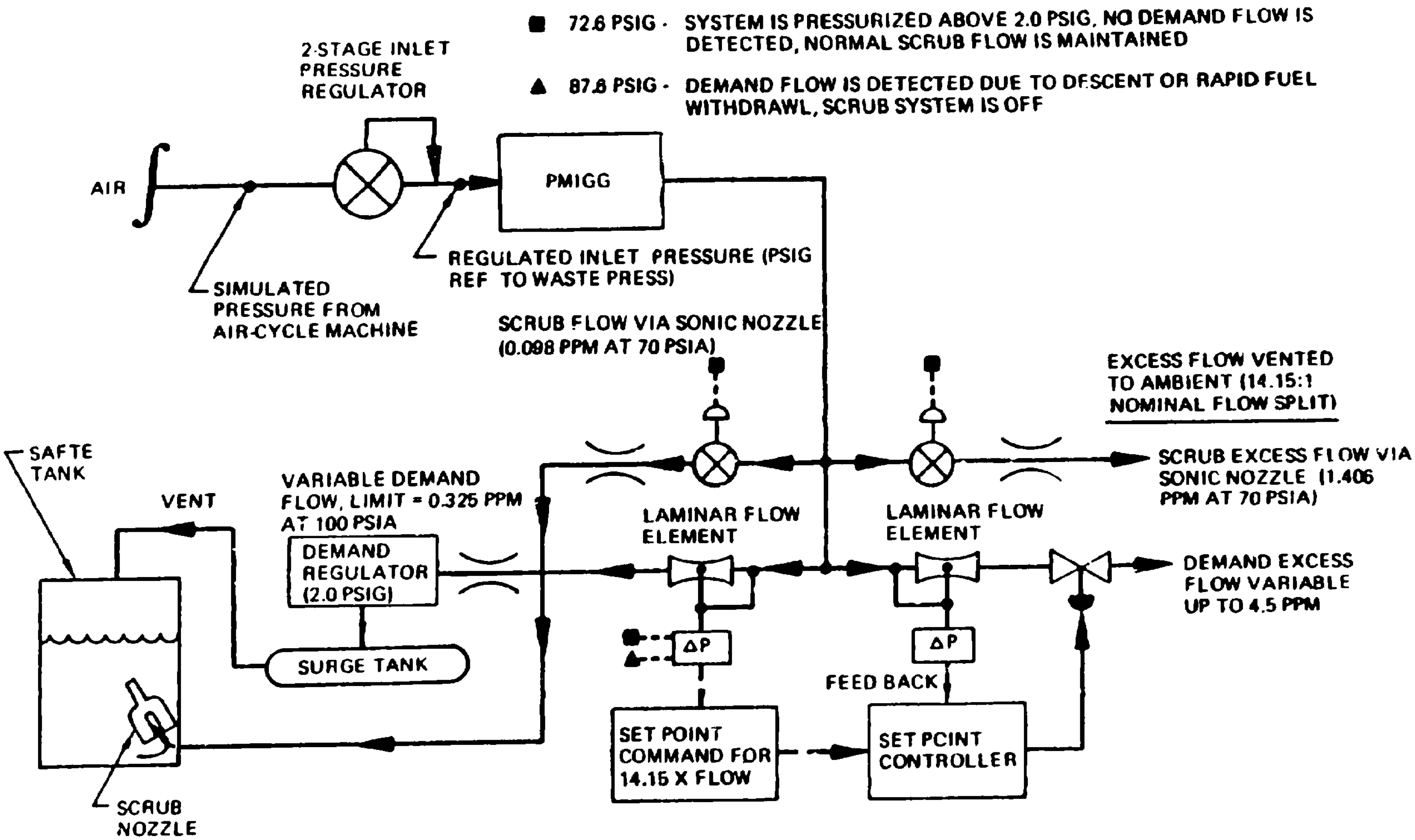


Figure 15. PMIGG Tank Pressure Control System

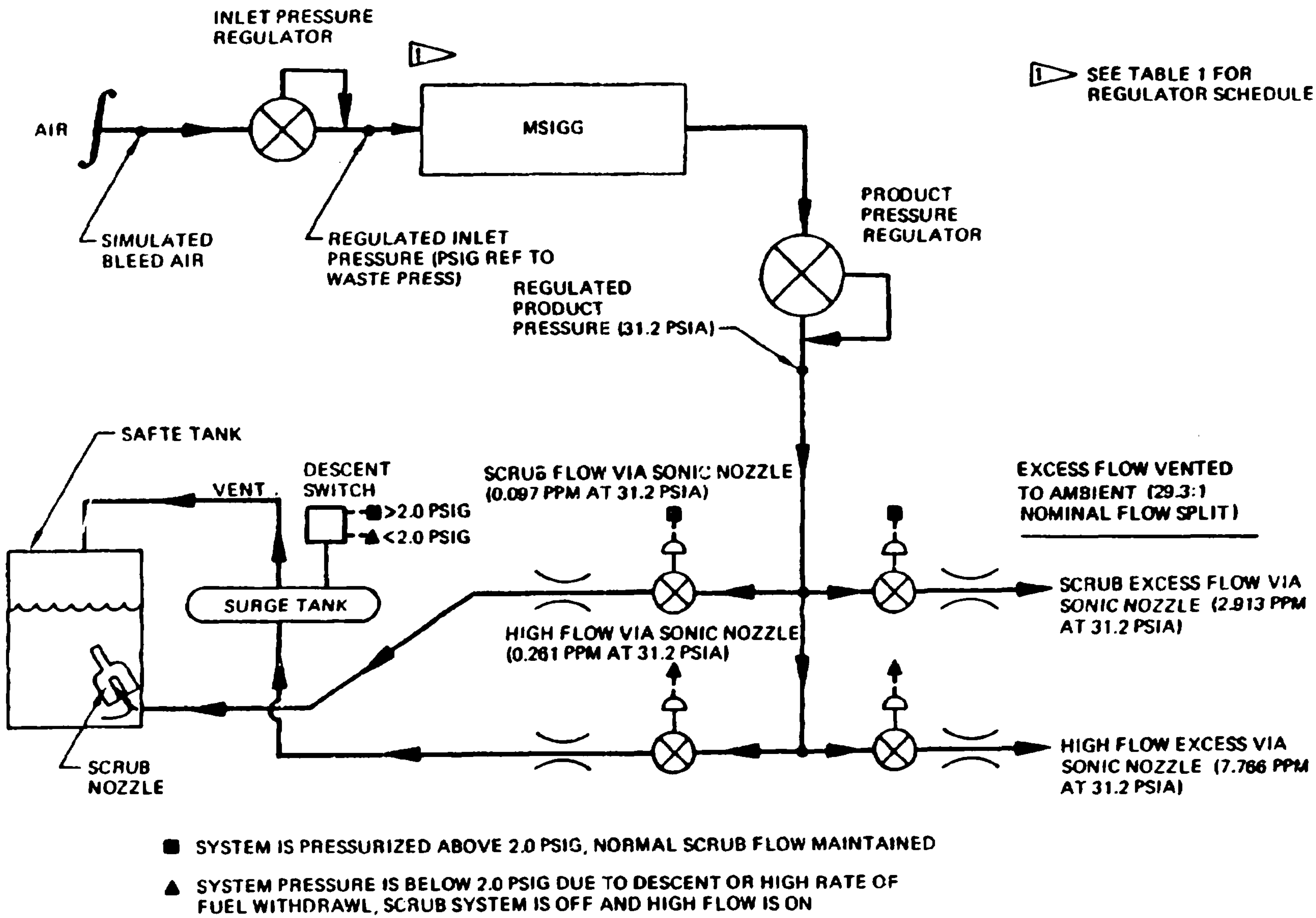


Figure 16. MSIGG Tank Pressure Control System

spectrometer. The position in the ullage at which the sample was obtained was controlled by a probe positioning system. Any one of the five ullage gas sample streams could be analyzed in quick succession by the mass spectrometer which provided data on the concentrations of nitrogen, oxygen, argon, and hydrocarbons.

3.4.2 Data Acquisition

The test data were processed and recorded with a ModComp data acquisiton system. A list of data channels associated with the IGG units and the mission simulations are tabulated in Table 2. All data channels were recorded for each steady state performance point and at regular intervals during a mission simulation. Data not suitable for computer recording, such as pressure fluctuation levels from the MSIGG, were recorded on an oscillograph. The computer acquired data were displayed in real time on two CRT screens for monitoring by the test director. The real time information on the CRT screens could be used to check any aspect of facility or IGG unit performance at any time. Printout could be obtained for selected data points or for an entire mission simulation. Data were first recorded temporarily on hard disc and later transferred to magnetic tape for permanent storage. The majority of the data from mission profiles were analyzed after first being plotted on a flat bed plotter. The plotting capability allowed conclusions on facility operation and IGG performance to be made in a timely manner.

Table 2. Test Instrumentation Description (1/2)

SUBSYSTEM	SENSOR DESIGNATION	TYPE	RANGE	VARIABLE NAME	COMMENTS/FUNCTION
BLEED AIR	PT-10	PSIG XDUCER	0-2500 PSIG	P-STOR	DELIVERY PRESSURE, BOTTLE FARM
	PT-7	PSIG XDUCER	0-640 PSIG	PLOFLO	NOZZLE PRESSURE FOR BLEED MASS FLOW
	TC-91	TYPE K-TC	0-100°F	TLOFLO	NOZZLE INLET TEMPERATURE FOR BLEED MASS FLOW
	T-301	TYPE T-TC	- 50°-100°F	THXOUT	CHILL AIR HX OUTLET TEMP.
	W-301	SONIC NOZZLE	17-37/9-22 PPM	WBLEED	BLEED FLOW RATE
	PT-8	PSIA XDUCER	0-160 PSIA	PBLEED	BLEED PRESSURE
	T-302	TYPE T-TC	- 50°-100°F	THTRIN	HEATER INLET TEMPERATURE
	T-304	TYPE T-TC	- 50°-350°F	THTROUT	HEATER OUTLET TEMPERATURE
	T-306	TYPE T-TC	- 50°-350°F	TINLET	IGG BLEED INLET TEMP.
	P-301	PSIG XDUCER	0-100 PSIG	PINLET	IGG INLET PRESSURE
	DP-304	DEWPOINT	- 35°-150°F	DWPT-M	IGG INLET DEWPONT (CHILLED MIRROR TYPE SENSOR)
WASTE	T-307	TYPE T-TC	40°-150°F	TWASTE	WASTE FLOW TEMPERATURE
	PT-4	PSIA XDUCER	0-15 PSIA	PWASTE	WASTE OUTLET PRESSURE
	PT-13	BAROMETER	26-31 IN HG	PBAROM	LOCAL BAROMETRIC PRESSURE
PRODUCT	0_2-301	OXYGEN ANALYZER	0-20.9%	OXPROD	BECKMAN OM-11 FOR PRODUCT CONCENTRT'N
	P-302	PSIA XDUCER	0-100 PSIA	PMNFLD	PRODUCT MANIFOLD PRESSURE
	T-308	TYPE T-TC	40° - 150°F	TMNFLD	PRODUCT MANIFOLD TEMPERATURE
	W-302	LAMINAR FLOW ELEMENT	0-.6 PPM	WDMI	PMIGG DEMAND FLOW TO SAFTE
	W-303	LAMINAR FLOW ELEMENT	0-10 PPM	WDMIEX	PMIGG DEMAND EXCESS FLOW
	W-304	SONIC NOZZLE	≈ 0.1 PPM	WSCR	SAFTE SCRUB FLOW
	W-305	SONIC NOZZLE	≈ 3.Ø PPM	WSCREX	SAFTE EXCESS SCRUB FLOW
	W-306	SONIC NOZZLE	≈ 0.26 PPM	WDM2	MSIGG HIGH FLOW TO SAFTE
	W-307	SONIC NOZZLE	≈ 7.7 PPM	WDM2EX	MSIGG EXCESS HIGH FLOW
	W-TOTAL	SUM OF ABOVE	0-10.0 PPM	WPROD	SUM OF W-302 TO W-307 (TOTAL PRODUCT FLOW)

Table 2. Test Instrumentation Description (2/2)

SUBSYSTEM	SENSOR DESIGNATION	TYPE	RANGE	VARIABLE NAME	COMMENTS/FUNCTION
SAFTE/KC-135 SIMULATOR	PT-101	PSIA XDUCER	0-14.7 PSIA	P-TANK	ALTITUDE TANK PRESSURE
↓	ΔP-305	PSID XDUCER	± 10 PSID	PSURGE	SURGE TANK RELATIVE PRESSURE
	0_2-302	0_2 ANALYZER	0-100%	OXFUEL	DISOLVED 0_2 PARTIAL PRES. SENSOR, FUEL
	...	TYPE J-TC	-40°-120°F	TWIDPM-TW6DPM	TEST TANK WALL TEMPERATURES
	...	TYPE J-TC	-40°-120°F	TULAGE	ULLAGE TEMPERATURE
	...	TYPE J-TC	-40°-120°F	T-FUEL	TANK BULK FUEL TEMPERATURE
	...	GPM FLOWMETER	0-3 GPM	GPMOUT	FUEL FLOW RATE AT OUTLET
	...	FLOWMETER SUM	0-573 Gallons	GALOUT	TOTAL FUEL EXPENDED
	...	POTENTIOMETER	0-1000 mm	MM--P1 thru PS	ULLAGE PROBE POSITION
	...	MASS SPECTROMETER	0-100%	%---HC	ULLAGE GAS ANALYSIS, CONTINUOUS ON-LINE
	...	MASS SPECTROMETER	0-100%	%---HC	ULLAGE GAS ANALYSIS, CONTINUOUS ON-LINE
	...	MASS SPECTROMETER	0-100%	%---N2	ULLAGE GAS ANALYSIS, CONTINUOUS ON-LINE
	...	MASS SPECTROMETER	0-100%	%---AR	ULLAGE GAS ANALYSIS, CONTINUOUS ON-LINE
MSIGG ONLY	P-501	PSIA XDUCER	0-100 PSIA	PREGOT	REGULATOR OUTLET PRESSURE
↓	P-502	PSIA XDUCER	0-100 PSIA	(Ograph Only)	BED PRESSURE
	P-503	PSIA XDUCER	0-30 PSIA	PWAMAN	WASTE MANIFOLD PRESSURE
	T-501	TYPE T-TC	40°-160°F	TREGOT	REGULATOR OUTLET TEMPERATURE
	T-502	TYPE T-TC	40°-160°F	TBDTOP	TOP BED TEMPERATURE
	T-503	TYPE T-TC	40°-160°F	TBDBOT	BOTTOM BED TEMPERATURE
	T-504	TYPE T-TC	40°-160°F	TWAMAN	WASTE MANIFOLD TEMPERATURE
	T-505	TYPE T-TC	40°-160°F	TBD-3	HIGH MIDDLE BED TEMPERATURE
	T-506	TYPE T-TC	40°-160°F	TBD-2	LOW MIDDLE BED TEMPERATURE
PMIGG ONLY	P-409	PSIG TRANSDUCER	0-100° PSIG	PREGOT	ASM INLET PRESSURE
↓	T-409	TYPE T-TC	75°F	TREGOT	ASM INLET TEMPERATURE
	T-410	TYPE T-TC	75°F	TPROD	PRODUCT TEMPERATURE
	T-411	TYPE T-TC	75°F	TPERML	WASTE MANIFOLD TEMP, LEFT SIDE
	T-412	TYPE T-TC	75°F	TPERMR	WASTE MANIFOLD TEMP, RIGHT SIDE

4.0 TEST PROCEDURES

The test program ground rules required PMIGG and MSIGG performance data for both steady state operation and simulated KC-135 airplane missions. The test procedures followed for each phase of testing are described below.

4.1 MSIGG Steady State Test Procedure

The first step in obtaining steady state performance data was to bring the entire MSIGG unit to thermal equilibrium at the desired temperature. This process required approximately 1 hour of operation at high product flowrates. Thermal equilibrium was determined by monitoring four thermocouples inserted into the sieve material of bed #1. These four thermocouples were spaced equally throughout the length of the bed. Prior to testing, all four thermocouples were required to have a total variation of not more than 5^{O}F. During all steady state tests of the MSIGG, the test variables (inlet pressure and temperature, waste pressure, and product flowrate) were controlled manually by adjusting the set point controllers until the desired values appeared on the CRT screens. For most steady state tests, the inlet pressure regulator was overridden; thus, the regulator remained wide open at all times allowing the bed inlet pressure to be controlled directly.

Since, during the operation of the MSIGG, the pressurization of each bed caused the inlet pressure to momentarily "sag", a test was conducted to determine the performance sensitivity to inlet pressure fluctuations. During these tests, orifice plates were installed in the inlet piping to simulate flow restrictions caused by a ram air heat exchanger that would be required in an actual aircraft installation.

4.2 PMIGG Steady State Test Procedure

The first step in obtaining a steady state performance data point was to bring the entire PMIGG unit to thermal equilibrium at the desired temperature. This process required up to 2 hours at high flow conditions. During all steady state tests of the PMIGG, the test variables (such as inlet pressure and temperature, waste pressure, and product flowrate) were manually controlled.

Set point controllers were adjusted until the desired values appeared on the CRT screens. For most steady state tests, the dual pressure regulator was overridden (causing it to remain wide open); therefore, ASM inlet pressure could be controlled directly.

4.3 MSIGG Test Procedure During Mission Simulations

During a mission profile, three variables were controlled while testing the MSIGG: inlet temperature, inlet pressure, and waste pressure. The inlet temperature profile was programmed to match the theoretical ram air heat exchanger outlet temperatures. This ram air heat exchanger was designed to regulate outlet temperatures to 40°F but could not maintain this temperature when free stream ambient was near or exceeded 40°F. A schedule of heat exchanger outlet temperature versus time was calculated, and the MSIGG inlet temperature was controlled to this schedule during the KC-135 mission simulation (see Appendix E).

The inlet pressure to the MSIGG was based on engine bleed air pressure minus the pressure drop through bleed piping and the ram air heat exchanger. These values were calculated, and a schedule of bleed pressure was developed for the KC-135 mission simulation (see Appendix E). The proper inlet pressure was obtained by adjusting a valve in the bleed air line to provide the same pressure decrease as the ram air heat exchanger.

The MSIGG waste pressure schedule simulated ambient pressure for the altitude of interest. The proper demand for product flow was provided automatically during a mission simulation by the two sonic nozzles for the scrub and high flow systems connected to the simulated KC-135 fuel tank.

4.4 PMIGG Test Procedure During Mission Simulations

During a mission profile, three variables were controlled for the PMIGG tests: inlet pressure, inlet temperature, and waste pressure. The air cycle machine, as designed, provided a constant outlet temperature of 75°F. The air cycle machine outlet pressure, however, depended on many variables. A simplified algorithm was devised to allow the computer based control system to dynamically compute (during the actual mission simulation) the inlet pressure set point as a function of altitude and descent switch setting (see Appendix E). This scheme was necessary because accurate predictions of the time when the descent switch settings would change were not possible. The waste pressure schedule simulated ambient pressure for the altitude of interest. The proper demand for product flow was provided automatically during a mission simulation by the scrub system and the demand regulator as the mission simulation proceeded.

5.0 TEST RESULTS

5.1 MSIGG Performance Test Results

5.1.1 Steady State Performance Envelope

The performance characteristics of the MSIGG, using the standard steady-state test procedure, are presented in Figure 17. Appendix F is a compilation of raw data for all steady state MSIGG tests. There are two fundamental trends to note:

- The product oxygen concentration decreased as the bed inlet pressure increased but with a steadily diminishing return.
- For a given inlet pressure the product oxygen concentration increased as the product flow rate increased.

The effects of temperature on MSIGG performance are shown in Figure 18 for 3 and 8 PPM flow rates. Data at other flow rates exhibited the same trends. As noted in Figure 18 the oxygen concentration in the product stream increased markedly with increasing temperature while the recovery showed only a slight increase (product flow rate held constant).

Attempts to operate the MSIGG at temperatures below 30°F were unsuccessful due to valve malfunctions. These valve malfunctions also occurred at certain combinations of high temperature and high pressure.

The effect of altitude on MSIGG performance is shown in Figure 19. As indicated in the figure, an improvement in product quality (lower O_2 concentration) occurred as operating altitude increased. The improvement was greatest at lower input operating pressures (20 to 30 psig) and almost negligible at 55 psig. There was also a slight increase in recovery at higher altitudes. The performance improvement at altitude means that the IGG can be operated at a lower pressure and still maintain acceptable NEA quality and flow rate.

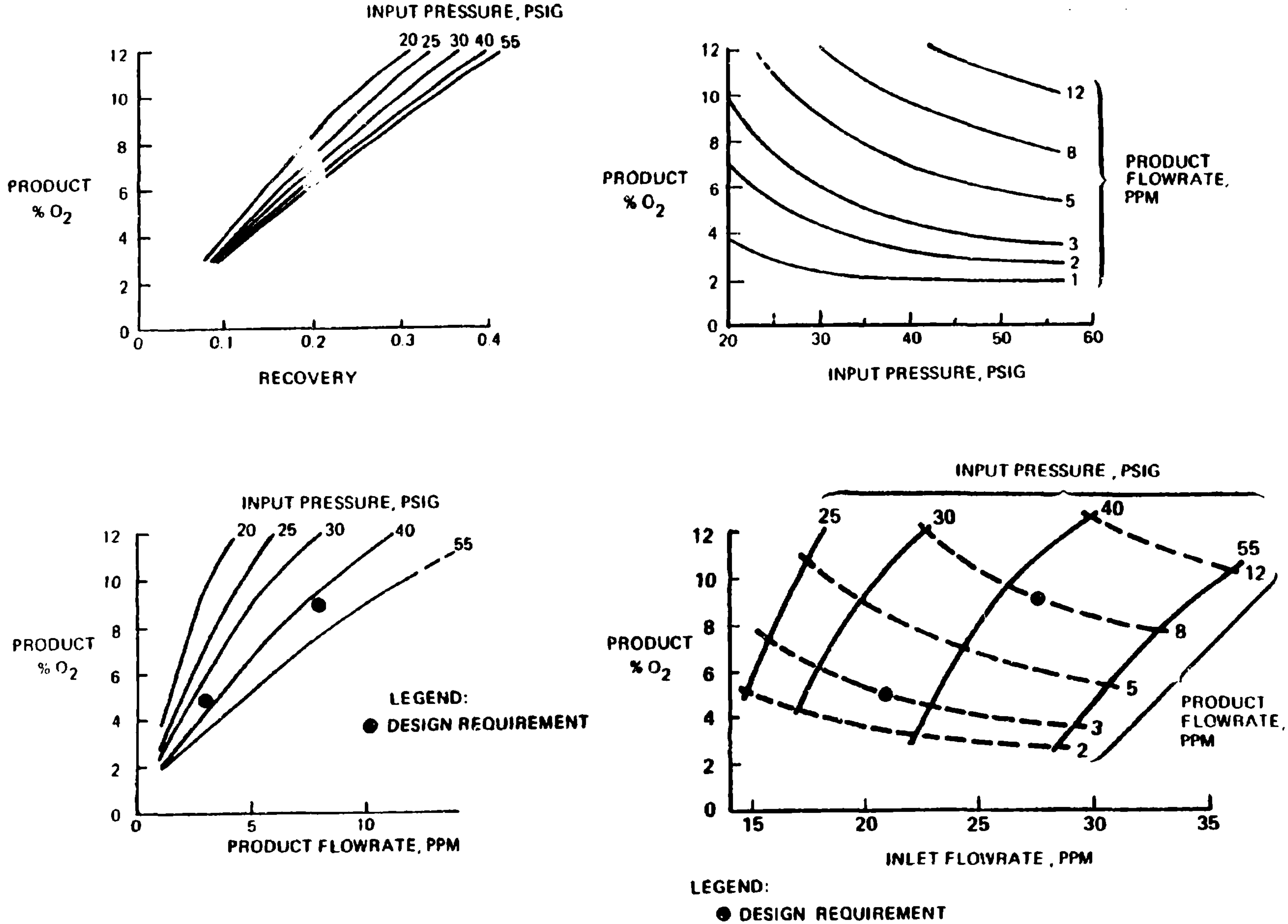


Figure 17. MSIGG Basic Performance at 75° F, Sea Level

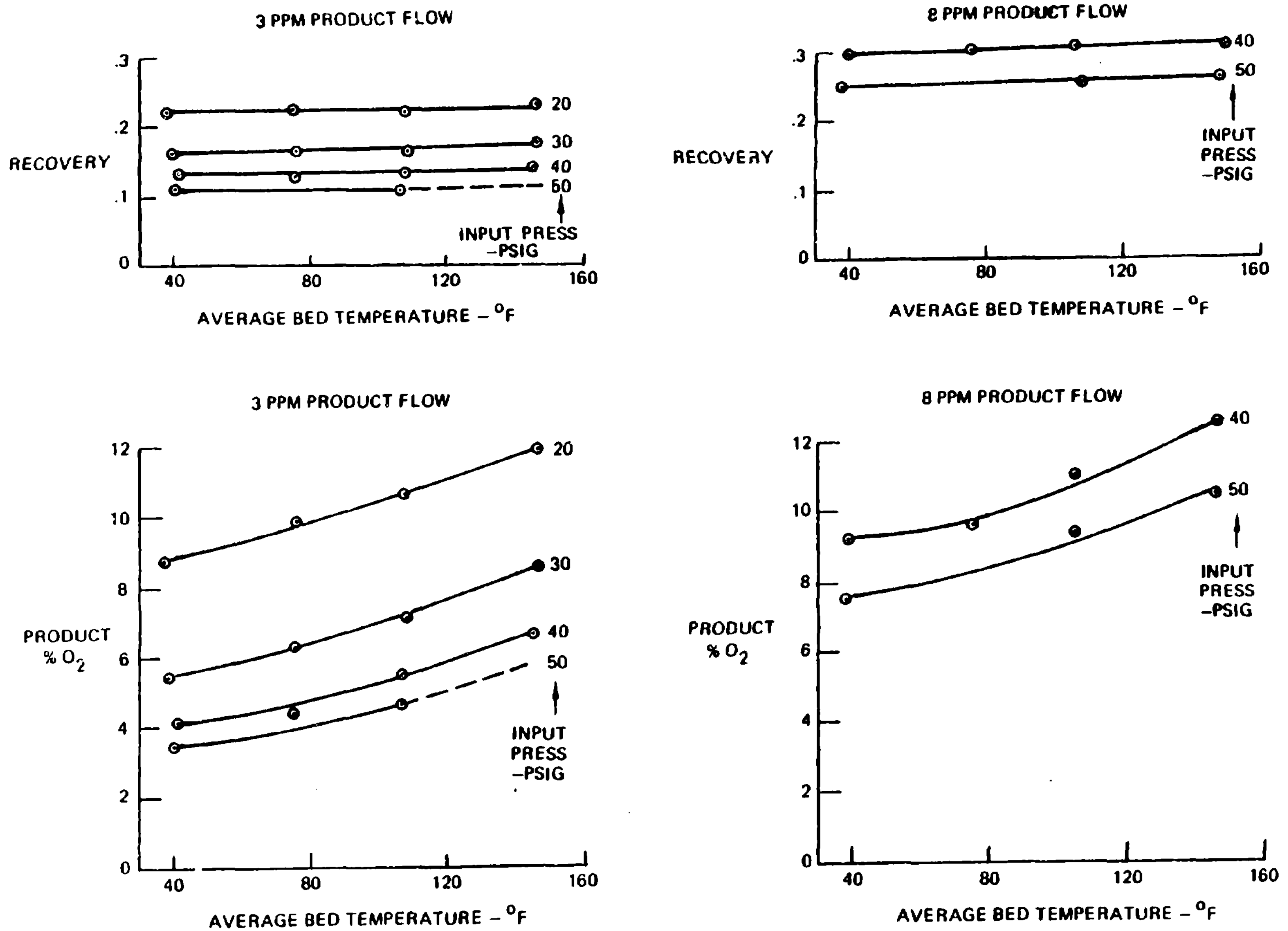


Figure 18. MSIGG Temperature Sensitivity

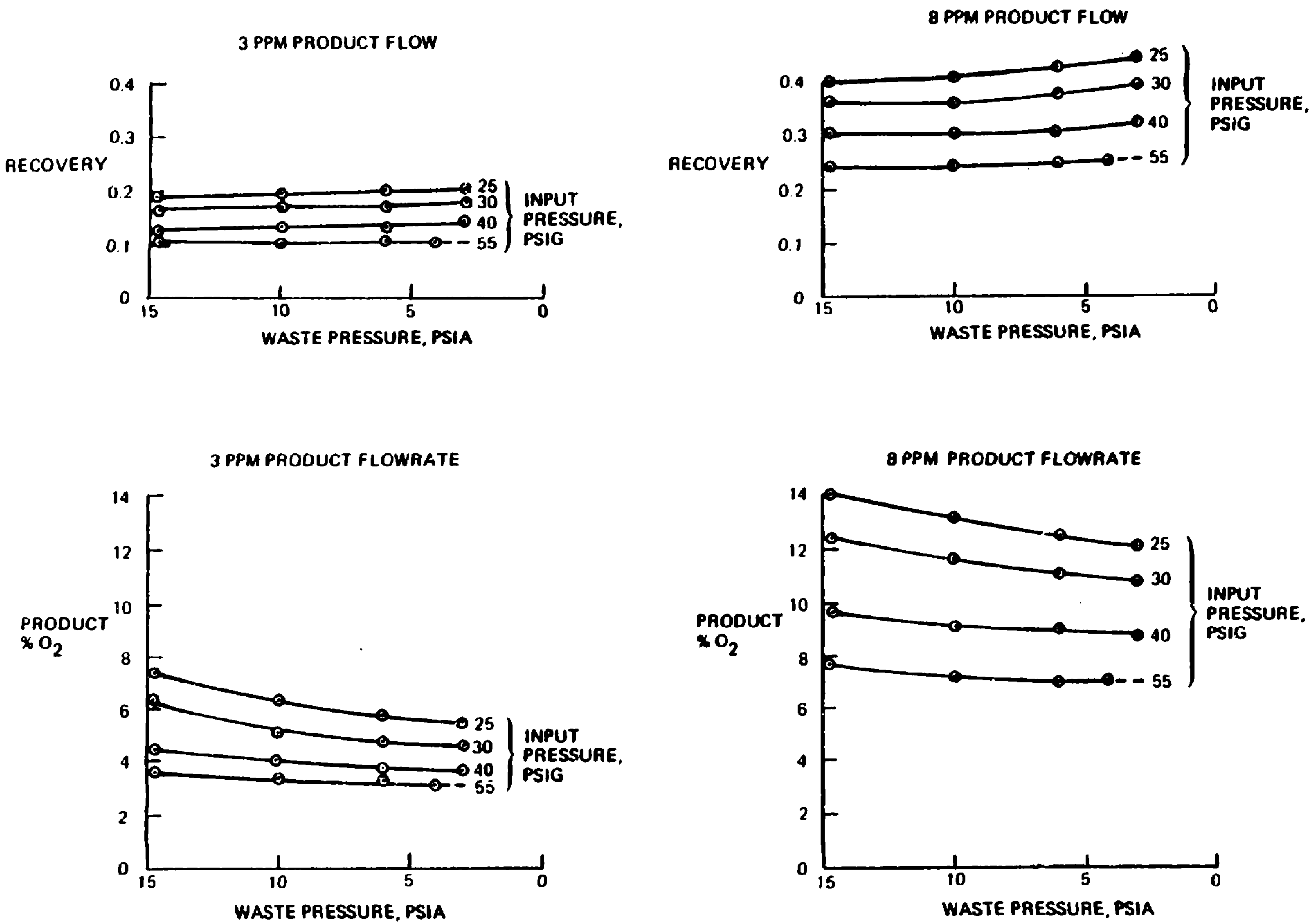


Figure 19. MSIGG Waste Pressure Sensitivity

5.1.2 Moisture Sensitivity

The objective of this series of tests was to determine if the MSIGG performance degraded due to poisoning of the sieve material by water in the bleed air. The sieve material, 4A zeolite (also used to dry compressed air), will preferentially adsorb water over oxygen. Concern was expressed that water in the bleed air will permanently poison a portion of the zeolite and degrade performance.

From Reference 5, the highest ambient moisture content anticipated for military aircraft is 180 grains of water/lb of dry air; the highest ambient moisture content anticipated for military aircraft. Ambient moisture is compressed and heated by the engine compressor, but no condensation occurs until the bleed air is cooled below the dew point by the ram air heat exchanger. The set-up used for these tests produced IGG inlet temperatures, pressures, and dew points matching those downstream of the ram air heat exchanger. Detailed information is available in Appendix C.

Table 3 is a summary of the test conditions and procedures used. These tests were designed to assess the transient, steady state, and permanent degradation caused by moisture in the bleed air. These tests began with the least severe test (i.e. lowest moisture content) and gradually changed procedures until the IGG had been tested under the most severe conditions that could be envisioned in actual aircraft operation.

All of the moisture tests involved the following procedure:

- Establish dry steady state performance at the desired input pressure, temperature, and product flowrate.
- Bring the inlet dew point to the desired level and maintain for a period necessary to achieve equilibrium.
- Return to the initial dry steady state performance.

For all of these tests the product oxygen concentration was used to monitor any changes in performance. Results from a typical moisture test are shown in Figure 20. Detailed results from all the moisture tests are provided in Appendix C.

Table 3. Summary of MSIGG Moisture Test Conditions

Temp (F°)	Dew Point (°F)	Moisture Content (Grains) [1]	Product Flow (PPM)	Test Procedure [3]	Description
75	60	22.8	8	A	Dry-Near Saturated-Dry
100	90	62.1	8	A	Dry-Near Saturated-Dry
120	110	115.8	8	A	Dry-Near Saturated-Dry
120	110	115.8	3	A	Dry-Near Saturated-Dry
120	120	156.7 [2]	8	B	Dry-Near Saturated-Dry
40-120	120	156.7 [2]	8	C	Cold Dry - Hot Saturated - Dry
40-120	120	156.7 [2]	8	D	Cold Dry - Hot Saturated - Wet Shutdown-Dry 16 Hours
40-120	120	156.7 [2]	8	D	Cold Dry - Hot Saturated - Wet Shutdown-Dry 5 Days
40-120	120	156.7 [2]	8	D	Cold Dry - Hot Saturated - Wet Shutdown-Dry 3 Days

[1] Moisture content of the bleed air, in the vapor phase, in grains per pound of dry air.

[2] For all saturated tests, additional liquid water was collected from the coalescer filter at the rate of 30 to 40 grains per pound of dry air. This resulted in a total (vapor + liquid) moisture content of 190 to 200 grains.

(Inlet pressure was 35.7 PSIG and waste gas vented to ambient for all tests.)

[3] See Appendix C for description of procedures.

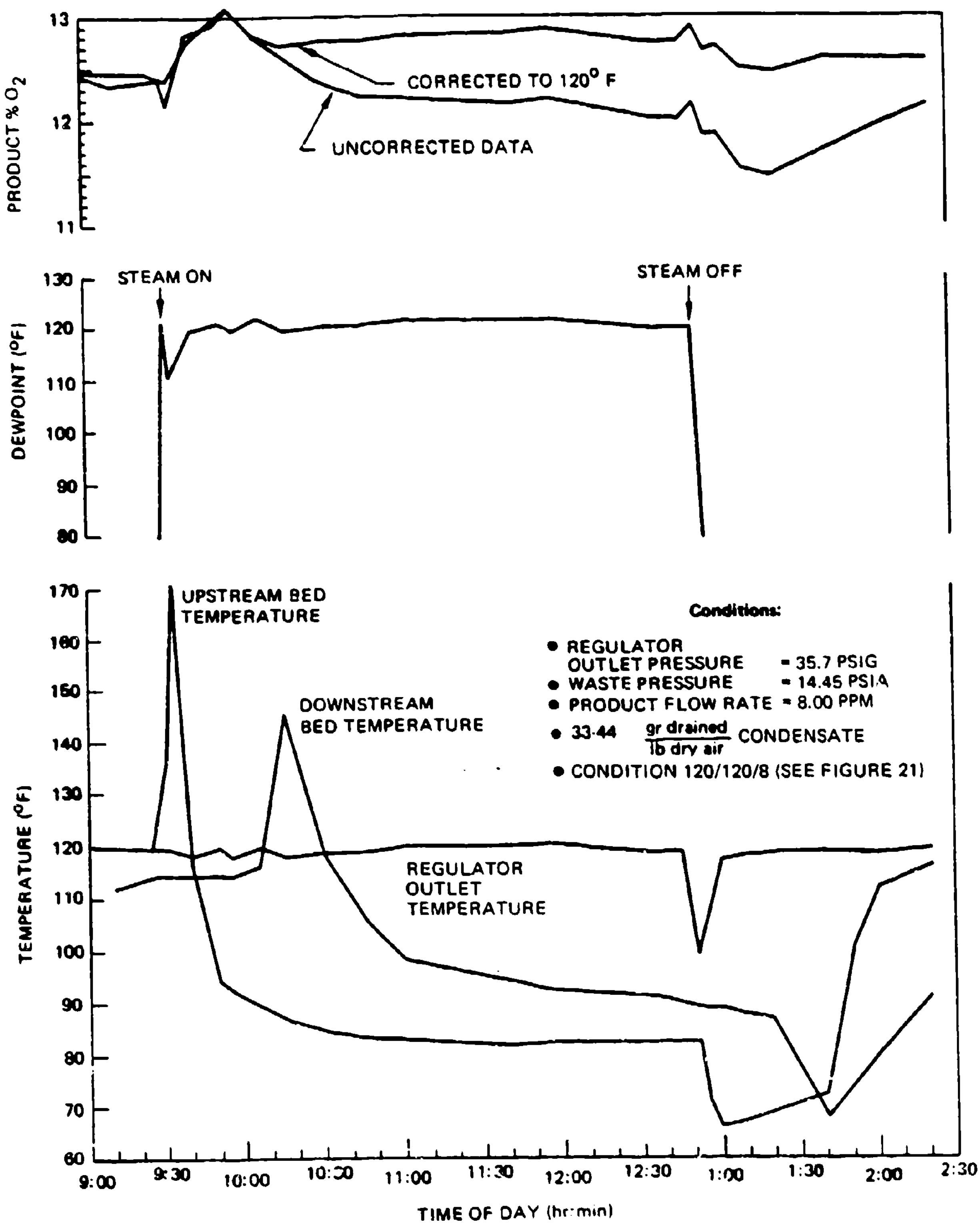


Figure 20. Typical MSIGG Moisture Test Results

A summary of the moisture test results is presented in Figure 21 and Table 4. Figure 21 summarizes the transient and steady state changes in MSIGG performance during the period of time when the bleed air contains significant quantities of water. Note that as bleed air moisture content is increased, the change in product oxygen concentration becomes greater until inlet conditions reach saturation.

A single test was conducted at 3 PPM to determine if product flow affects the sensitivity to moisture. As can be seen in Figure 21, the performance change at 3 PPM versus 8 PPM is reduced exactly by the ratio of 3/8. This ratio suggests that at higher product flowrates, water is driven farther into the beds and reduces the efficiency (temporarily) of more sieve material.

Table 4 summarizes the performance, before and after each moisture test, at 120^{o}F with dry air and 8 PPM product flowrates. Note that the corrected product oxygen concentration varies with no definite trend, indicating a certain amount of data scatter. From the data in Table 4, it is difficult to draw any conclusion about a permanent change in performance. The amount of data scatter observed, even though test variables were carefully controlled, presents problems when looking for trends. Larger changes in performance must be observed before any definite conclusions can be drawn. An analysis of the accuracy and repeatability of the MSIGG product oxygen measurement is included in Appendix D. This analysis indicates that product oxygen measurement repeatability (test to test) would be no better than $\pm 0.2\%$ O_2 and could be worse when considering the MSIGG valve problems and measurement problems associated with measuring fluctuating pressures.

The following results may be observed based on a review of the data tables and plots mentioned:

- o The MSIGG performance does temporarily degrade due to unsaturated moisture levels in the bleed air. Performance returns to normal with dry bleed air.
- o Saturated or super-saturated bleed air moisture levels actually cause a performance improvement due to a drop in bed temperature.
- o Significant bed temperature changes are produced when bleed air moisture levels are changed or reach saturation.

Condition	$\left(\frac{gr}{lb\ dry\ air}\right)$	Maximum gross Δ% O_2 during initial transient	Steady state, temperature corrected, Δ% O_2
75/60/8	22.8	+0.30	+0.15
100/90/8	62.1	+0.56	+0.24
120/110/8	115.8	+0.80	+0.40
120/120/8 (saturated)	156.7 gr vapor 33-44 gr drained	+0.70	+0.39
120/110/3	115.8	+0.30	+0.15

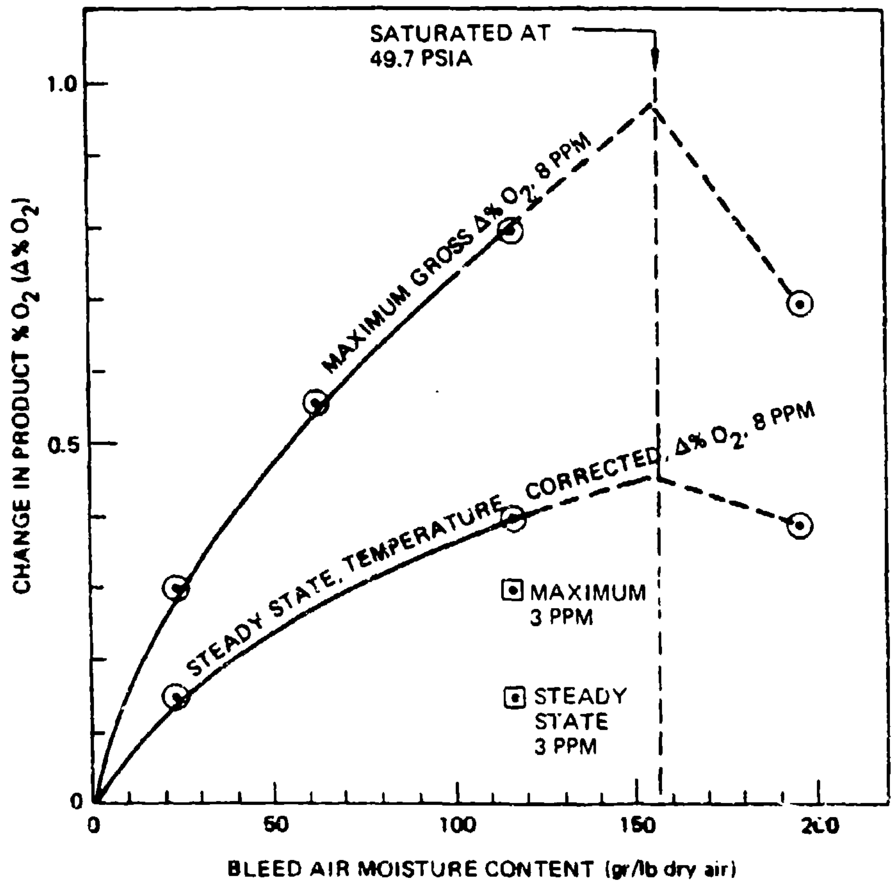


Figure 21. MSIGG Moisture Produced Transient Performance Change

Table 4. Summary of MSIGG Moisture Test Results

Date	Test Condition	Product % O_2 [1]
13 Dec 83	120/110	12.62 (Before) 12.57 (After)
16 Dec 83	120/120	12.44 (Before) 12.62 (After)
19 Dec 83	40-120/120	12.47 (After)
20 Dec 83	40-120/120	-
	Off 16 Hrs	-
21 Dec 83	120° Dry	12.58 (After)
22 Dec 83	40-120/120	-
	Off 5 Days	-
27 Dec 83	120° Dry	-
6 Jan 84	120° Dry	12.86 (After)
6 Jan 84	40-120/120	-
	Off 3 Days	-
9 Jan 84	120° Dry	12.74 (After)

PRODUCT % O_2 CORRECTED TO:

[1] REGULATOR OUTLET PRESSURE = 35.7 PSIG
PRODUCT FLOWRATE = 8 PPM
AVERAGE BED TEMPERATURE = 120°F
WASTE PRESSURE = 14.40 PS1A

- No significant permanent shift in performance was observed during the 2 months of moisture tests.
- The tests conducted were probably not adequate to determine if moisture will cause long term degradation. With the product oxygen repeatability problems encountered, a long term moisture sensitivity test (lifetime of MSIGG) is required to determine if longer term degradation is taking place.

5.1.3 Performance vs. Operating Hours

The performance of the MSIGG was periodically checked in tests conducted from 19 August 1982 through 19 January 1984. Steady state performance was determined at various combinations of inlet pressures and product flowrates. A comparison of these data at different times was used to identify long term performance changes over the 387 hours of MSIGG operation. An analysis of these data is presented in Figures 22 and 23. Several trends were noted as operating hours accumulated on the MSIGG:

- The inlet pressure required to produce a specific product flow and oxygen concentration generally increased with time and showed a marked increase after the moisture tests (Figure 22).
- The bleed air flow rate (input to the MSIGG) for a fixed inlet pressure and product flowrate steadily decreased with time (Figure 23). These changes were significant and occurred throughout the entire MSIGG test program, not just after the moisture tests.
- Even with the changes in bleed air pressure and flowrate noted above, the productivity (input/output ratio at fixed product oxygen concentration) remained largely unchanged. Even though the MSIGG required a higher inlet pressure, the MSIGG did not require an increase in bleed air flow to produce a specific product flowrate and oxygen concentration (Figure 22).

As discussed in Section 2.2, the MSIGG utilized a separate inlet and exhaust valve for each of the eight beds for a total of 16 valves. These valves proved to be unreliable as they were designed. On several occasions, either a complete failure or sluggish operation of the valves was encountered. The inlet and exhaust valves were specially developed by Clifton Precision for

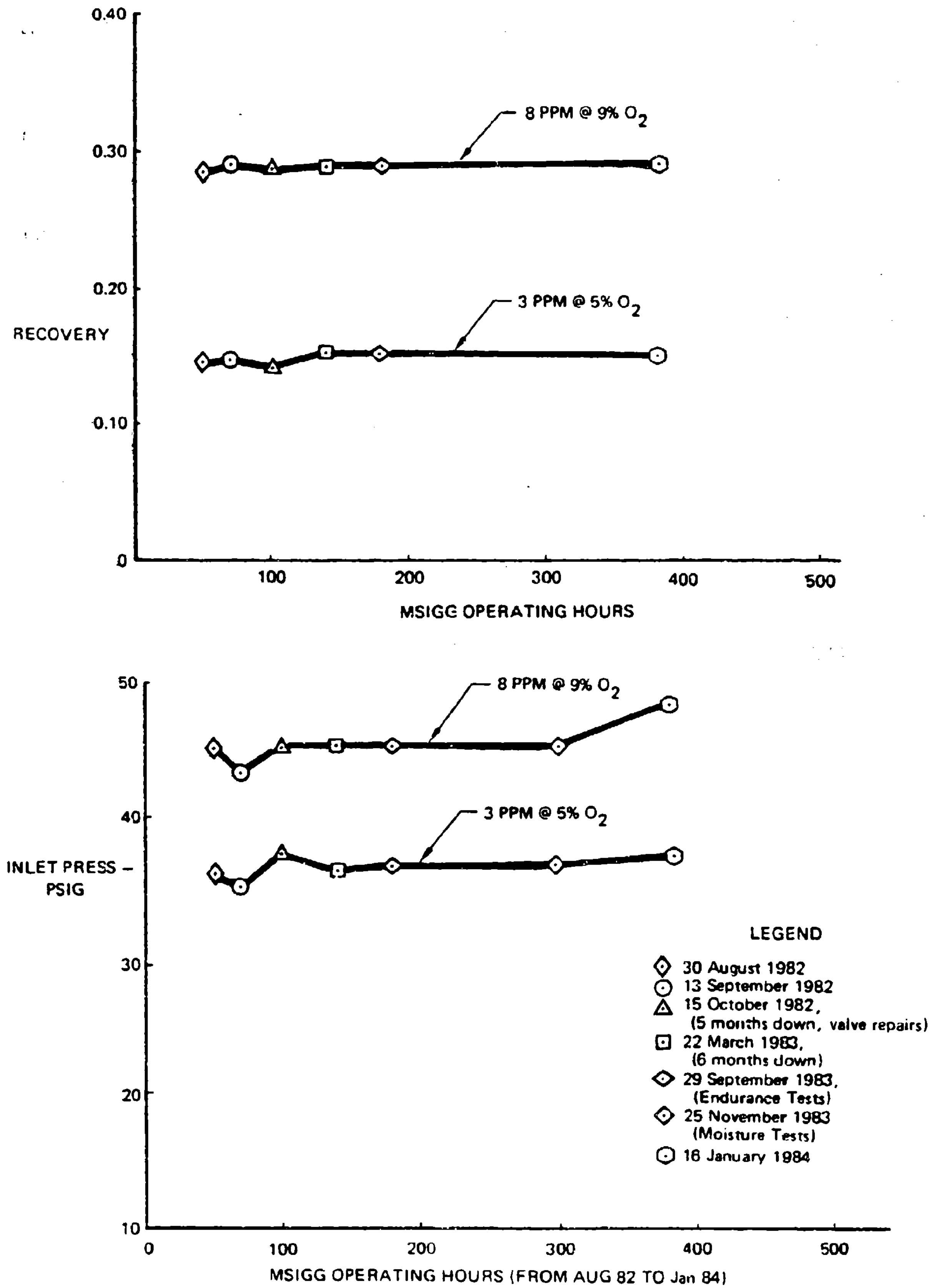


Figure 22. MSIGG Performance VS Operating Hours

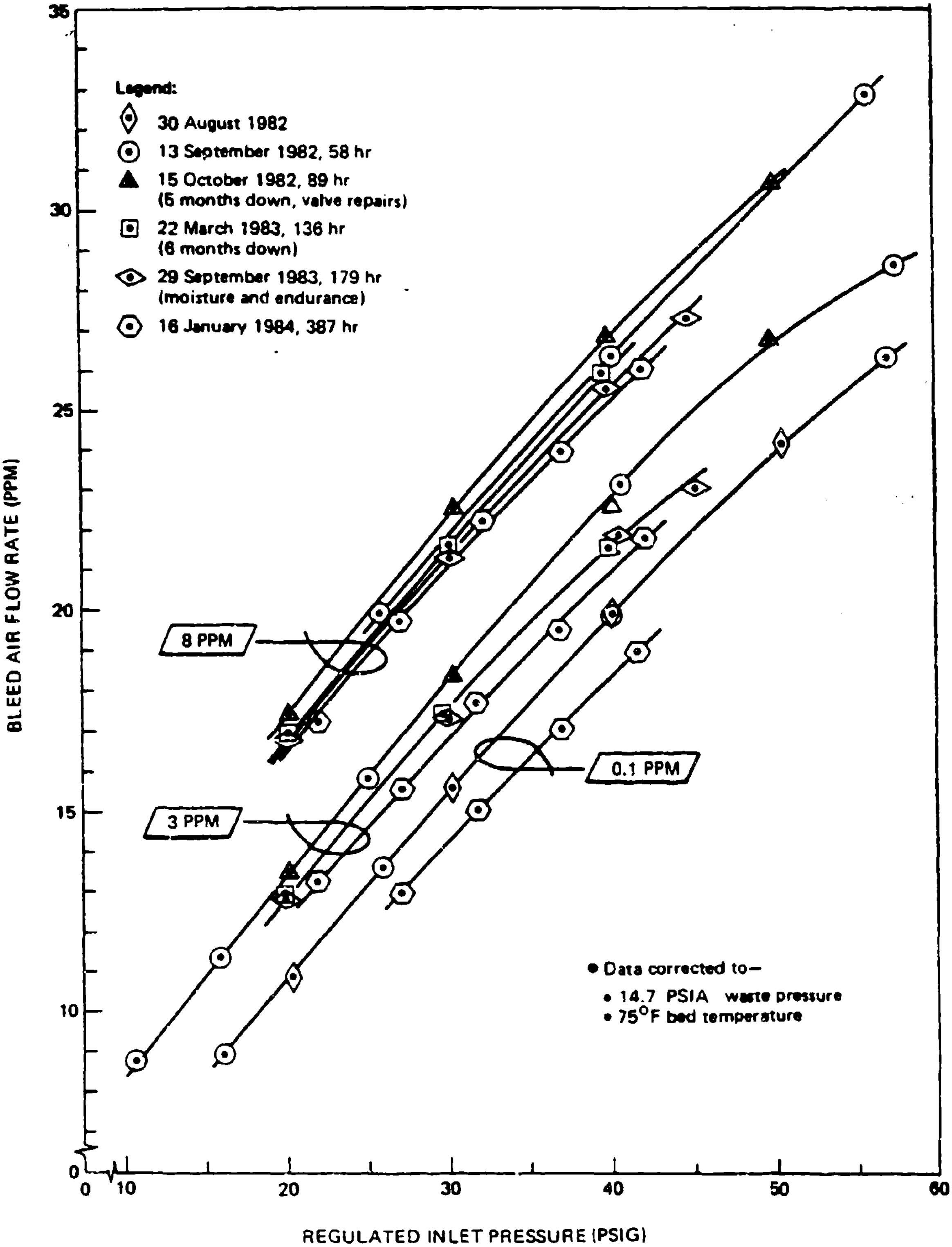


Figure 23. Changes in MSIGG Bleed Air Requirements

this application. Each valve was a fast response, high flow, pilot operated, diaphragm valve. The pilot valve was a small commercial solenoid valve installed in the body of the main valve. After the first valve failures were encountered, the main diaphragm valves were redesigned and modified by Clifton Precision. This redesign succeeded in eliminating some of the problems with the main diaphragm valve but subsequent test experience indicated that diaphragm life is approximately 100-200 hours (50,000 - 100,000 cycles). The commercial solenoid pilot valves caused erratic operation of the main diaphragm valves throughout the entire test program, requiring frequent disassembly, cleaning, and lubrication in order to obtain repeatable performance data. These particular pilot valves proved to be completely unacceptable for this application.

5.1.4 Discussion of Performance Changes

A theory is offered here to explain observations. Throughout the test series (not just during moisture tests), moisture entered the MSIGG and contaminated progressively more sieve material. The moisture entered via the inlet air or through open or removed valves. The water molecules permanently occupied sites in the sieve material and thereby reduced the ability of the sieve to adsorb oxygen molecules. This moisture contamination caused the beds of the MSIGG to have progressively less effective sorbant area and is consistent with the observed drop in bleed air flow at a specific inlet pressure. Note in Figure 23 that at product flowrates of 0.1 PPM (effectively zero), the decrease in bleed flow suggests that the beds could not hold as many adsorbed gas molecules and thus the beds operate as if they were smaller.

5.2 PMIGG Performance Test Results

5.2.1 Steady State Performance Envelope

The performance of the PMIGG was evaluated under steady state conditions to determine the effects of inlet pressure, temperature, altitude, and product flow rate on recovery and product oxygen concentration. Basic performance tests were repeated periodically throughout the duration of the entire test program in order to track any loss in performance. The initial basic performance is presented in Figure 24. Appendix G is a compilation of raw

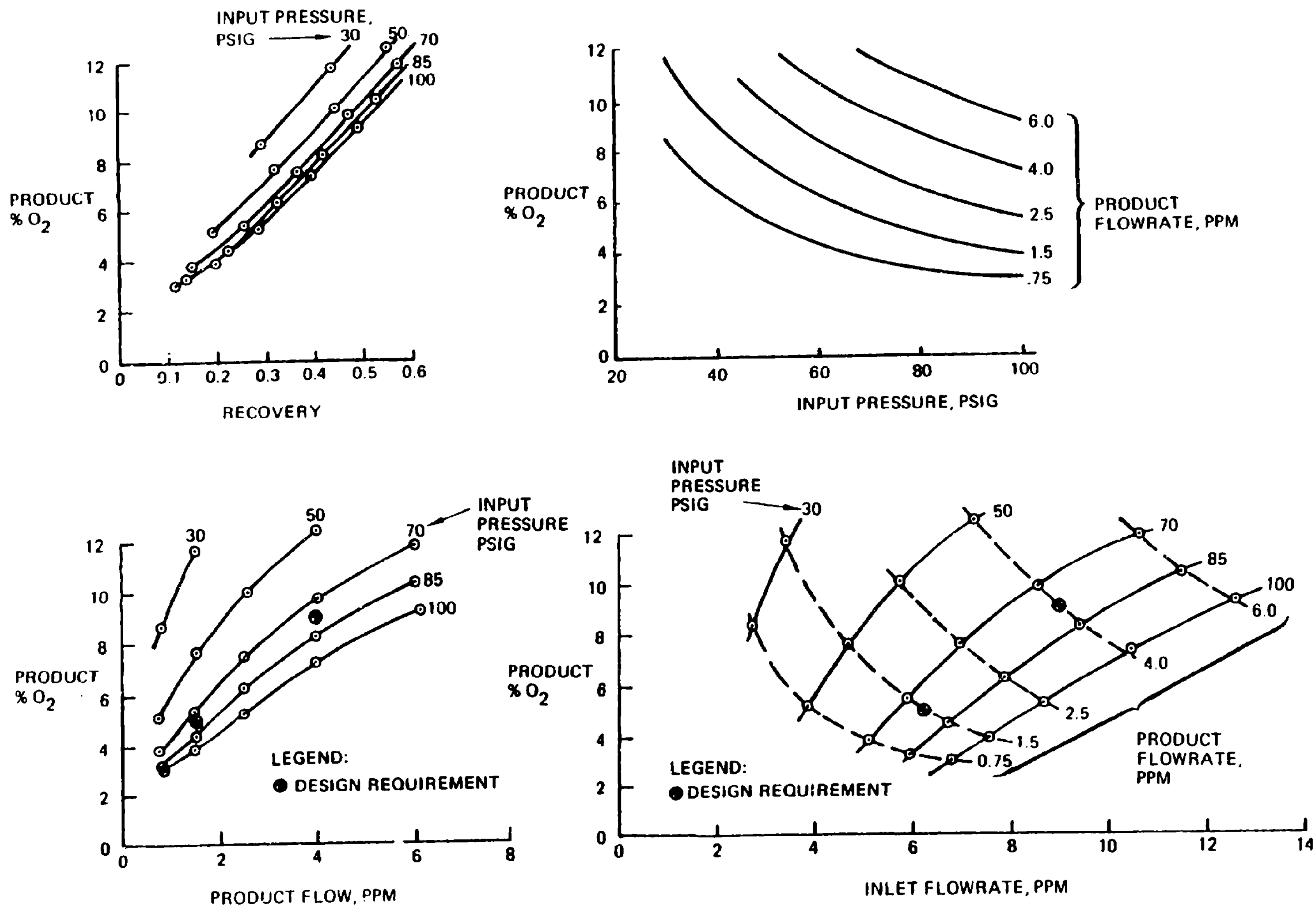


Figure 24. PMIGG Basic Performance at 75° F, Sea Level

data for all steady state PMIGG tests. There are two fundamental trends to note:

(1) As inlet pressure is increased, the product oxygen concentration decreases but with a steadily diminishing return.

(2) As product flow rate increases, the product oxygen concentration increases.

The effect of temperature on PMIGG performance is shown in Figure 25 for product flow rates of 1.5 and 4.0 PPM. Data at other flow rates exhibit the same trends. Note that as temperature is increased, the performance improves (i.e. the product oxygen concentration decreases) but the recovery decreases. The manufacturer has chosen 75°F as the operating point based on a trade-off of performance, efficiency and fiber life. The fiber life is reduced at higher temperatures and pressures (Reference 1). Consequently, no attempt was made to operate the PMIGG at temperatures above 75°F.

The effect of altitude on PMIGG performance, at 1.5 and 4.0 PPM product flow rates, is shown in Figure 26. Note that at operating pressures of 75 to 80 psig, there is only a slight improvement in performance as the waste pressure is decreased. This means that the performance is a function of only the operating pressure difference between inlet and waste and is independent of altitude.

5.2.2 Moisture Sensitivity

The PMIGG was tested over a wide range of inlet air moisture contents in order to assess the effect on PMIGG performance. The following areas were investigated:

- The effect of moisture on module productivity and recovery.

- The effect of moisture on module differential pressure (inlet - product pressure).

- The moisture separation efficiency of the PMIGG (product gas dew point versus inlet gas dew point).

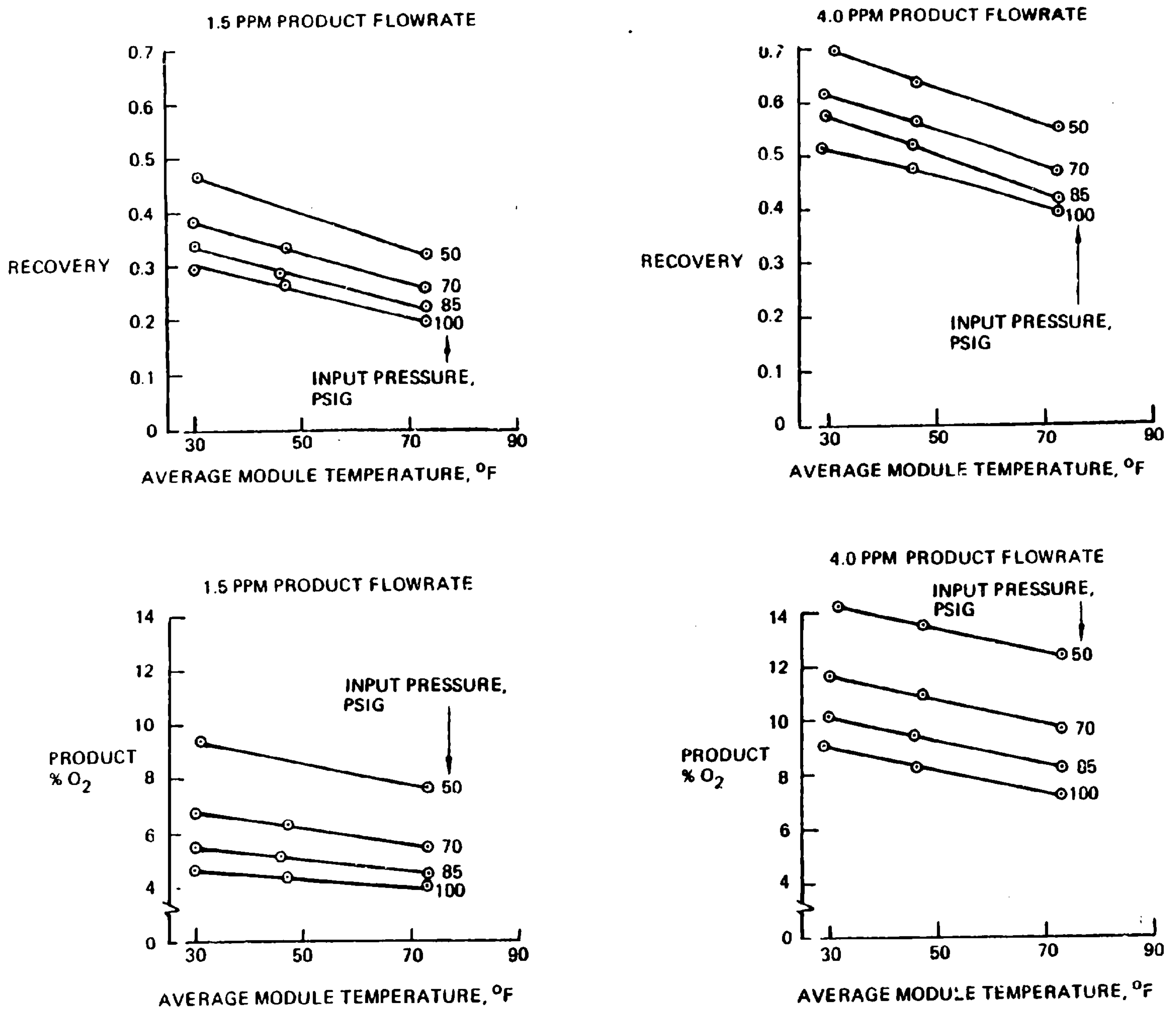


Figure 25. PMIGG Temperature Sensitivity

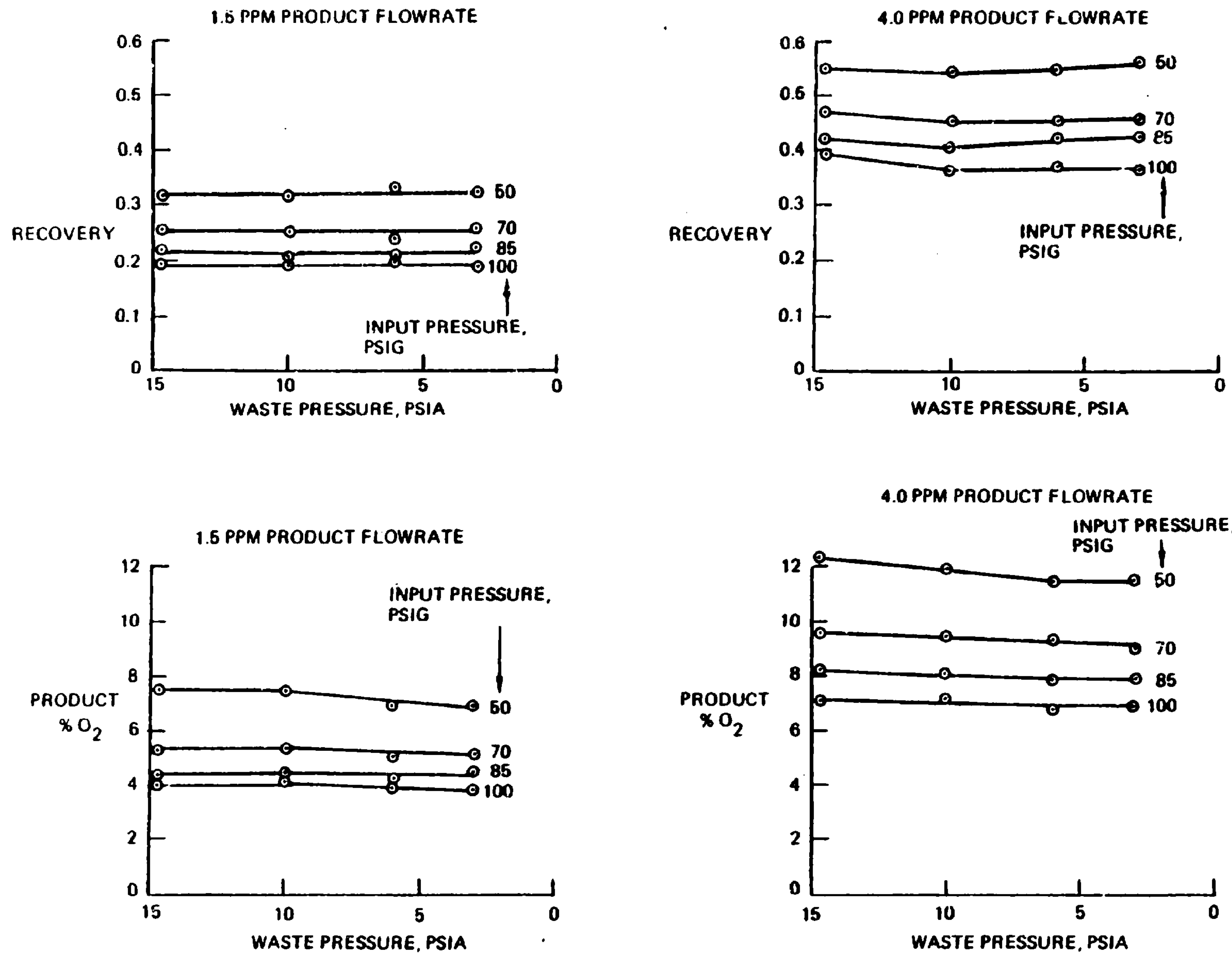


Figure 26. PMIGG Waste Pressure Sensitivity

Tests were conducted with the inlet air dew point near saturation as well as saturated. Steam was added to the inlet air until the desired dew point was obtained at the inlet to the PMIGG. The PMIGG performance and product dew point were then recorded. During tests with saturated inlet air, liguid water was collected at a measured rate from the water extractor, filter housing, and filter outlet.

The results of PMIGG moisture tests are presented in Table 5 and can be summarized as follows:

- Moisture does not measurably affect productivity, efficiency, or module differential pressure.

- The PMIGG does separate moisture to a limited degree. The product gas moisture content ranged between 7 and 33 percent of the inlet air moisture levels.

Table 5. PMIGG Moisture Test Results

INLET AIR MOISTURE CONTENT			INLET AIR TEMP °F	PMIGG PERFORMANCE CORRECTED PRODUCT FLOW RATE (PPM) [1]	PRODUCT MOISTURE CONTENT		COMMENTS
ENTERING WATER EXTRACTOR	LEAVING WATER EXTRACTOR						
GRAINS/LB OF DRY AIR	GRAINS/LB OF DRY AIR	DEW POINT °F			GRAINS/LB OF DRY AIR	DEW POINT °F	
<0.25	-	-	76	3.64	-	-	BASELINE DATA WITH DRY INLET AIR
11.3	11.3	60.6	79	3.65	0.76	-0.8	NEAR SATURATED INLET AIR, NO CONDENSATE
90.2	22.2	80.3	79	3.55	7.5	48.6	SUPER-SATURATED INLET AIR
135.8	24 8	83.6	87	3.62	5.3	40.1	SUPER-SATURATED INLET AIR, WET OVERNIGHT SHUTDOWN
<0.25	-	-	76	3.50	-	-	POST MOISTURE TEST DATA WITH DRY AIR

[1] PMIGG Product Flow Capacity Corrected to:
85.5 PSIG Inlet Pressure
75°F Inlet Temperature
9% Product $\%O_2$

5.2.3 Endurance Tests and Performance Degradation

5.2.3.1 Performance Versus Operating Hours

Numerous performance tests were performed on the PMIGG over a 19-month period from December 1982 through August 1984. The tests involved performance sensitivity to such variables as inlet pressure, inlet temperature, inlet moisture, altitude, product flow rate, and also included mission simulations and endurance tests. Throughout the PMIGG test program, the performance of the PMIGG was monitored by repeatedly conducting a basic performance test. Data from these tests are presented, in Figure 27, as product flow, waste flow, and recovery versus operating hours. A gradual shift in performance is evident as operating hours were accumulated. A near continual degradation in performance is evident for the first 272 hours of operation (down to 71% of initial performance).. The PMIGG manufacturer suspected that the degradation problem was partially due to a relaxation of the wrapping material which holds the fibers in a tight bundle. After the manufacture of these permeable membrane modules, the manufacturer developed an improved wrapping material.

Another suspected cause of degradation was an unbalanced condition between the five modules. Optimum performance is obtained if each module has the same product gas oxygen concentration. It was decided to re-balance the five modules, to determine what portion of the degradation was attributable to an unbalanced condition, if any. The results at 276 operating hours indicated that a significant amount of the observed degradation was regained by a simple re-balance (back to 82% of initial performance).

The five modules were then retrofitted by the manufacturer with the improved wrapping material. The immediate effect of the new wrapping material is shown at 290 operating hours, bringing the PMIGG performance back to within 90% of initial performance. The effect of retrofitting with the improved wrapping material is also shown in Table 6 as individual module performance before and after the re-wrap.

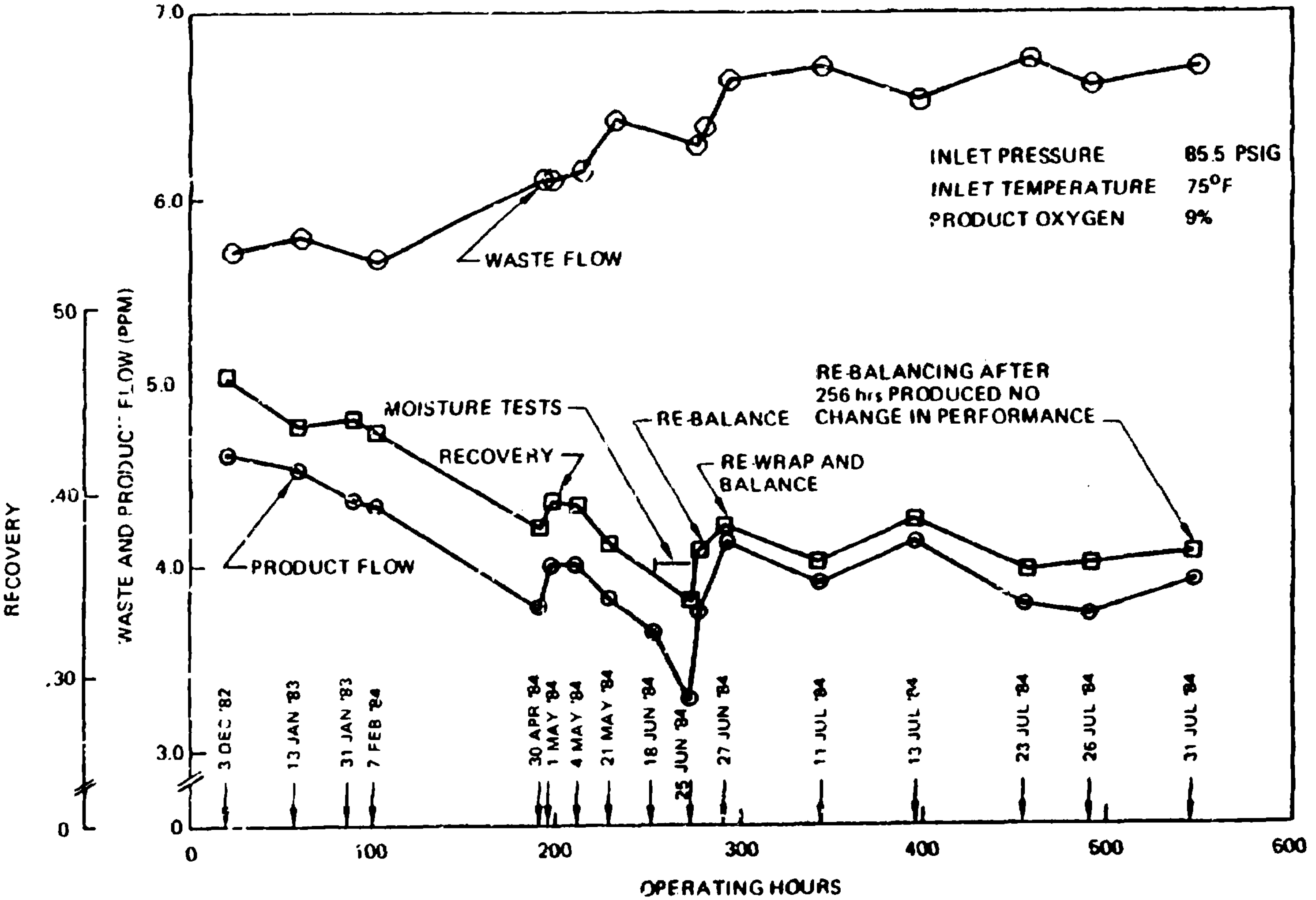


Figure 27. PMIGG Performance VS Operating Hours

Table 6. Individual Module Performance Before and After Re-Wrap [2]

MODULE IDENTIFICATION	ORIGINAL MANUFACTURER'S DATA [1]	BEFORE RE-WRAP 27 JUNE 84 276 OPERATING HOURS		AFTER RE-WRAP 29 JUNE 84 290 OPERATING HOURS	
	(PPM)	(PPM)	(% OF ORIGINAL)	(PPM)	(% OF ORIGINAL)
LMF 1	0.843	0.685	81.3	0.750	89.0
LMF 2	0.810	0.797	98.4	0.798	98.5
LMF 3	0.855	0.836	97.8	0.867	101.4
LMF 4	0.826	0.742	89.8	0.831	100.6
LMF 5	0.883	0.779	88.2	0.844	95.6
TOTAL	4.217	3.839	91.0	4.090	97.0

[1] Johnson, R. L., Gillerman, J. B., AIRCRAFT FUEL TANK INERTING SYSTEM, AFWAL-TR-82-2115, July 1983

[2] Product Flow Capacity at:
85.5 PSID Inlet Pressure
75°F Inlet Temperature
9% Product O_2 Concentration

To determine if the improved wrapping material would prevent further degradation, an additional 250 hours of operation were accumulated. Performance tests were conducted approximately every 50 hours. These data are presented in Figure 27 between 290 and 546 operating hours. While these data show slight variations in performance (both up and down), there was no significant change; and the earlier trend of performance degradation was halted.

5.2.3.2 Performance Versus On-Off Cycles

At the time the five permeable membrane modules were re-wrapped, the manufacturer indicated that degradation can be significantly affected by rapid increases in inlet pressure during start-up. No prior indication of this problem was given in Reference 1 or otherwise. Indeed, the manufacturer has now indicated that start-up time is the single most significant variable affecting fiber lifetime. During the first 272 hours of operation, the PMIGG had undergone many ON-OFF cycles with the inlet pressure rise time being an uncontrolled and unrecorded variable. It is likely that during this period, many start-up cycles were fast enough to cause degradation. To assure that this problem did not recur during the endurance tests from 290 to 546 hours, start-up cycles were done gradually over a 50-second period, to determine the effect of operating hours only. The PMIGG, as designed by the manufacturer, was intended to be started by a quick opening valve at the inlet to the modules. To demonstrate a definite sensitivity to rapid inlet pressure rises, tests were performed monitoring performance versus the number of ON-OFF cycles. During these tests a ball valve immediately upstream of the modules was quickly opened to produce rapid inlet pressure rise times (< 1 second). This rapid start-up is termed a "hard start." The unit remained pressurized for 30 seconds, after which time the inlet valve was closed for a 60 second period while the pressure vented to ambient. The total cycle time was 90 seconds resulting in a test which yielded 40 "hard start" ON-OFF cycles per hour. The data from the "hard start" ON-OFF cycle test are presented in Figure 28 and show a 38% drop in performance after only 250 cycles, confirming that "hard starts" should be avoided.

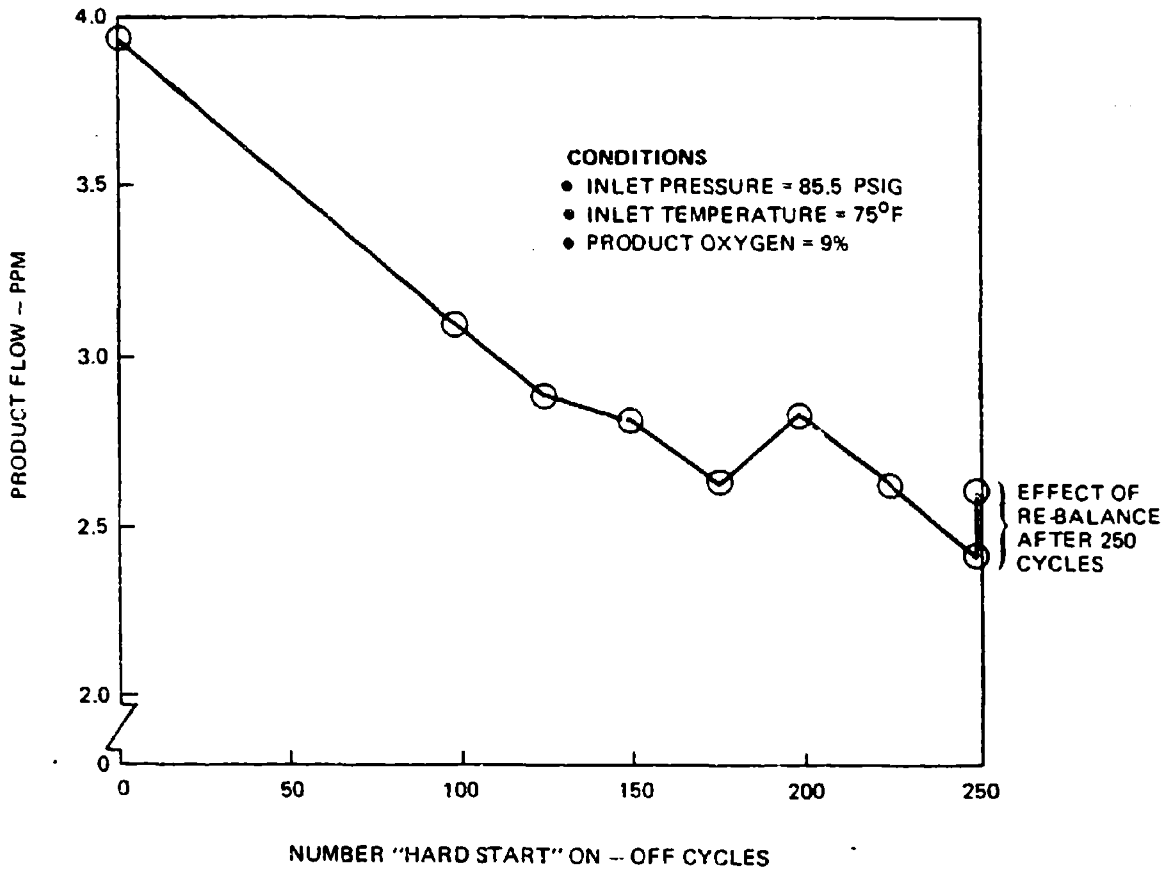


Figure 28. PMIGG Performance VS "Hard Start" On–Off Cycles

5.2.3.3 Discussion of Performance Changes

The data gathered during this test program indicate that the PMIGG is extremely sensitive to rapid pressure increases during start-up. These "hard starts" create excessively high pressure differentials across the fiber bundle, perhaps causing the fiber bundle to "balloon". The ballooning mechanically breaks fibers and/or causes flow channeling through the bundle.

The sensitivity to "hard starts" will require that a "soft start" (slowly increasing pressure) criterion be developed. This criterion demands that the mechanical valves and regulators upstream of the modules be designed to slowly increase inlet pressure. The PMIGG manufacturers may need to define a fiber bundle differential pressure that should not be exceeded during start-up.

5.2.4 Performance Tests of "New" PMIGG Modules

As a result of the performance degradation noted previously in this report, five (5) "new" PMIGG modules were obtained from DOW Checmical on a loan basis for the purpose of testing under conditions similar to those that caused the degradation of the original modules. DOW Chemical believed that the design and manufacturing refinements incorporated in the "new" modules would eliminate any of the degradation experienced previously.

The testing focused on three areas: (1) the performance envelope as compared to the "old units"; (2) the performance stability versus time without "on-off" cycling; and (3) the effect of "on-off" cycling using "soft starts". It was understood that start-up times must be much slower than were used in tests of the "old" modules.

5.2.4.1 Performance Versus Operating Hours

A total of 250 operating hours were accumulated on the "new" modules. This total includes the operating time required for the performance envelope and the cycle testing. Performance over this 250-hour period is shown in Figure 29 and indicates that the performance improved significantly after 20 hours of operation.

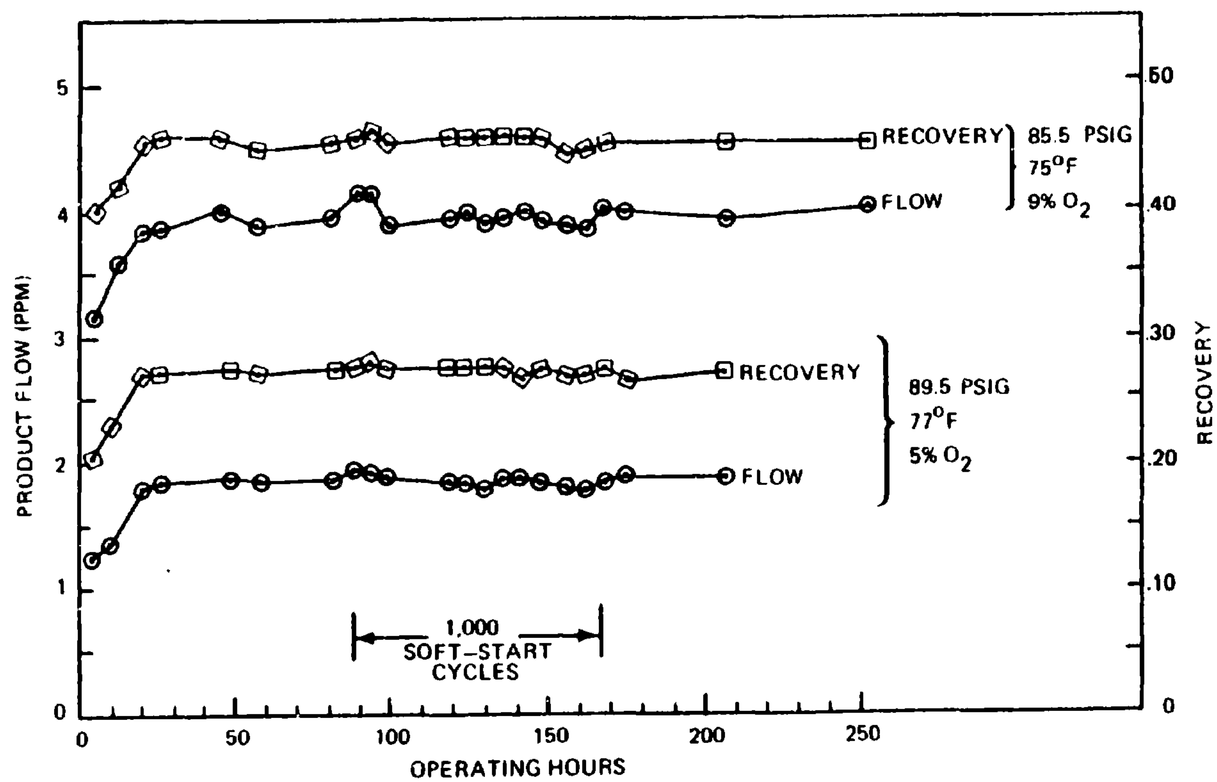


Figure 29. "New" PMIGG Performance VS Operating Hours

DOW believes that a period of non-use (approximately 2 months in this case) causes a temporary drop in performance which is recovered after a few hours of operation (20 hours in this case). The reason for this phenomenon is not known. Furthermore, this initial performance lag followed by improvement has not yet been shown to be repeatable. Additional testing may be required to fully characterize this phenomenon.

The performance data presented in Figure 29 indicates no discernible change in performance after the first 20 hours of operation. The degradation experienced previously with the "old" PMIGG modules is not evident over the 250 hours. Note that periods of non-use did not exceed 3 days during testing of the "new" PMIGG's.

5.2.4.2 Steady State Performance Envelope

Performance tests on the "new" PMIGG modules were performed as a means of directly comparing the performance of "new" versus "old" PMIGG modules. There were no altitude or temperature sensitivity tests performed since these trends were not expected to change. The raw data from these performance comparison tests are included in Appendix G. The performance of the "new" modules is directly compared to that of the "old" in Figure 30. Note that the performance of the "new" modules is not as good as the "old" modules before the "old" modules degraded. The tests were performed on the "new" modules after 80 operating hours had been accumulated and performance had stabilized.

5.2.4.3 Performance Versus ON-OFF Cycles

The adverse effect of "on-off" cycling was the primary motivating factor in deciding to perform tests on the "new" modules. The data on the "old" modules had previously established the fact that short start-up times (on the order of one second) produced a rapid deterioration in performance. The manufacturer believed that if the start-up time was lengthened, the degradation could be eliminated. DOW could not provide a fiber bundle differential pressure limit for the "soft start" cycle (i.e. how fast to open the inlet valve). However, it was felt that if, during start-up, the fiber bundle differential pressure did not exceed its steady state value, the "soft start" cycle should not produce any deterioration. Figure 31 describes the "soft start" cycle used

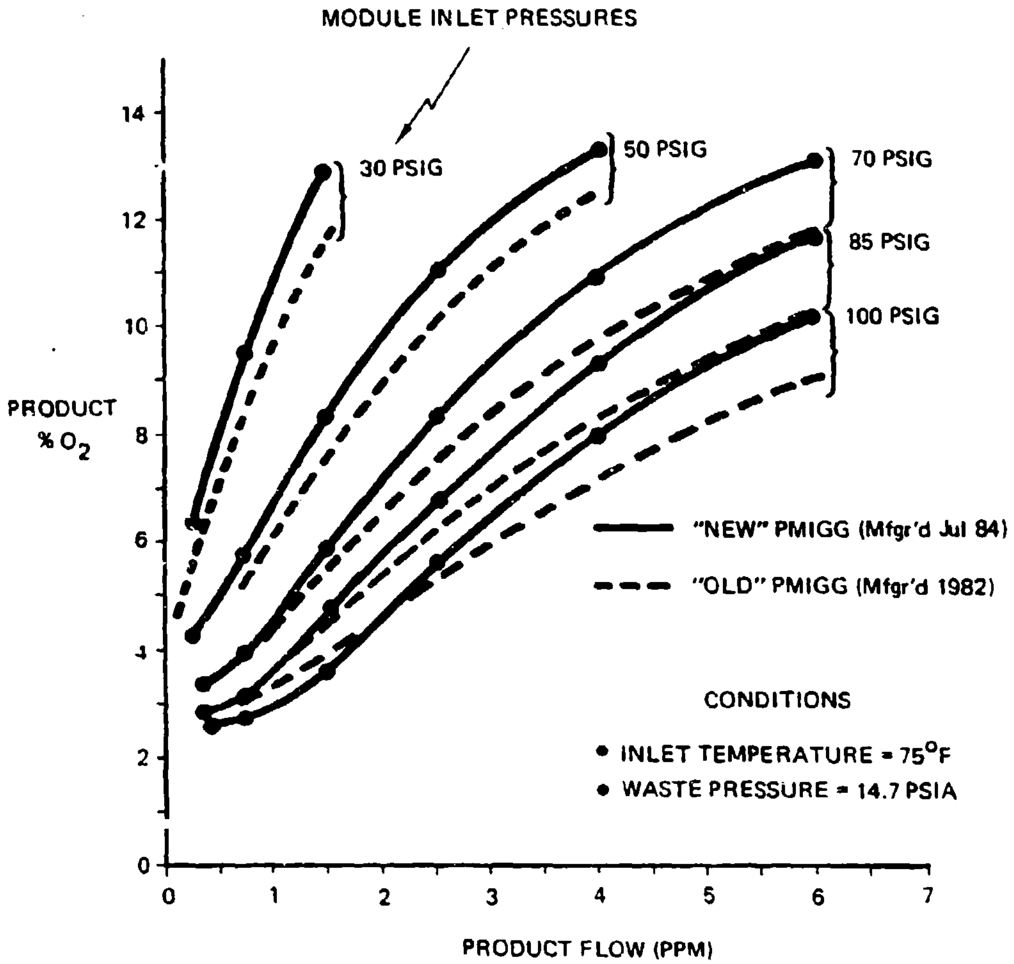


Figure 30. PMIGG "New" VS "Old" Performance Comparison

throughout these cycle tests. The "soft start" inlet valve was controlled so that it opened in 95 seconds. Faster valve opening times could not be used without exceeding the steady state module differential pressure. The entire "on-off" cycle required 95 seconds for the valve to open, 25 seconds of stable PMIGG operation, and 60 seconds with the inlet valve closed to allow the PMIGG to depressurize. This cycle was repeated at the rate of 20 cycles per hour via an automatic control system.

A total of 1000 cycles were accumulated using the "soft start" cycle described in Figure 31. Performance was measured at least every 100 cycles to detect any gradual degradation. The results of the 1000 cycle test are presented in Figure 32. There were no discernible changes in performance over the entire 1000 cycles.

5.2.4.4 Discussion of Results

The primary objective of these tests with the "new" PMIGG modules was to prove that "soft starts" would eliminate any degradation caused by "on-off" cycling. The results have supported this objective. However, shorter start-up times (i.e. < 95 seconds) would be useful in an aircraft application. There was no attempt made during these tests to determine the maximum allowable fiber bundle differential pressure during start-up. If start-up times on the order of 95 seconds are objectionable in certain aircraft applications, further testing may be required to optimize the start-up time.

The differences between "old" and "new" module performance are attributed to differences in design and construction. The "new" modules were designed to a slightly different specification by Dow.

There remains an unanswered question regarding the "break-in" phenomenon, and whether this phenomenon will be repeated each time the modules are unused for a period of time greater than a few days. The modules tested here had been "on-the-shelf" for approximately 2 months and required 20 hours of operation before acceptable performance was obtained. This need for a "break-in" period could not be tolerated in an aircraft application each time the PMIGG unit was "off" for a few days or weeks. Additional testing is required to fully characterize this phenomenon.

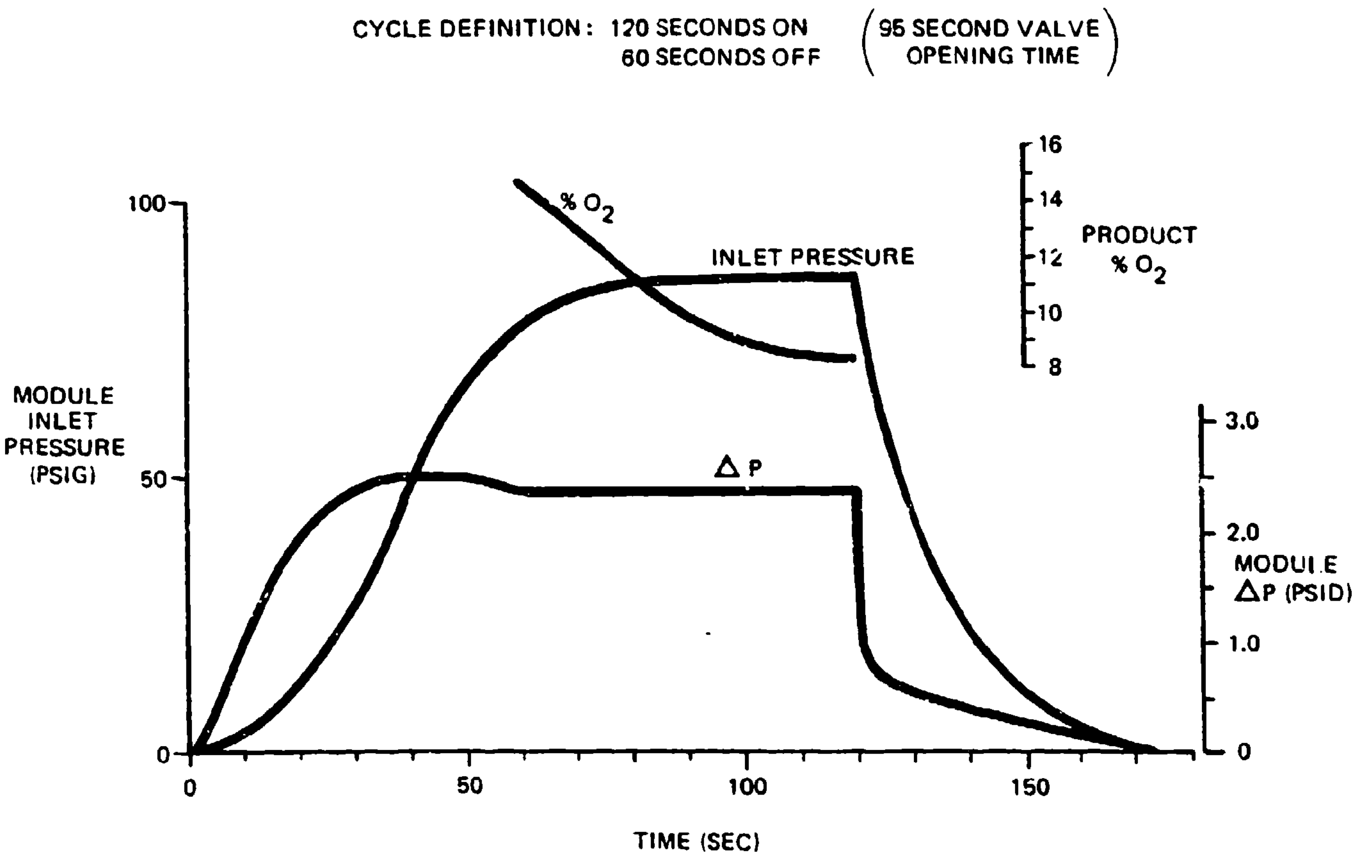


Figure 31. PMIGG "Soft Start" Cycle

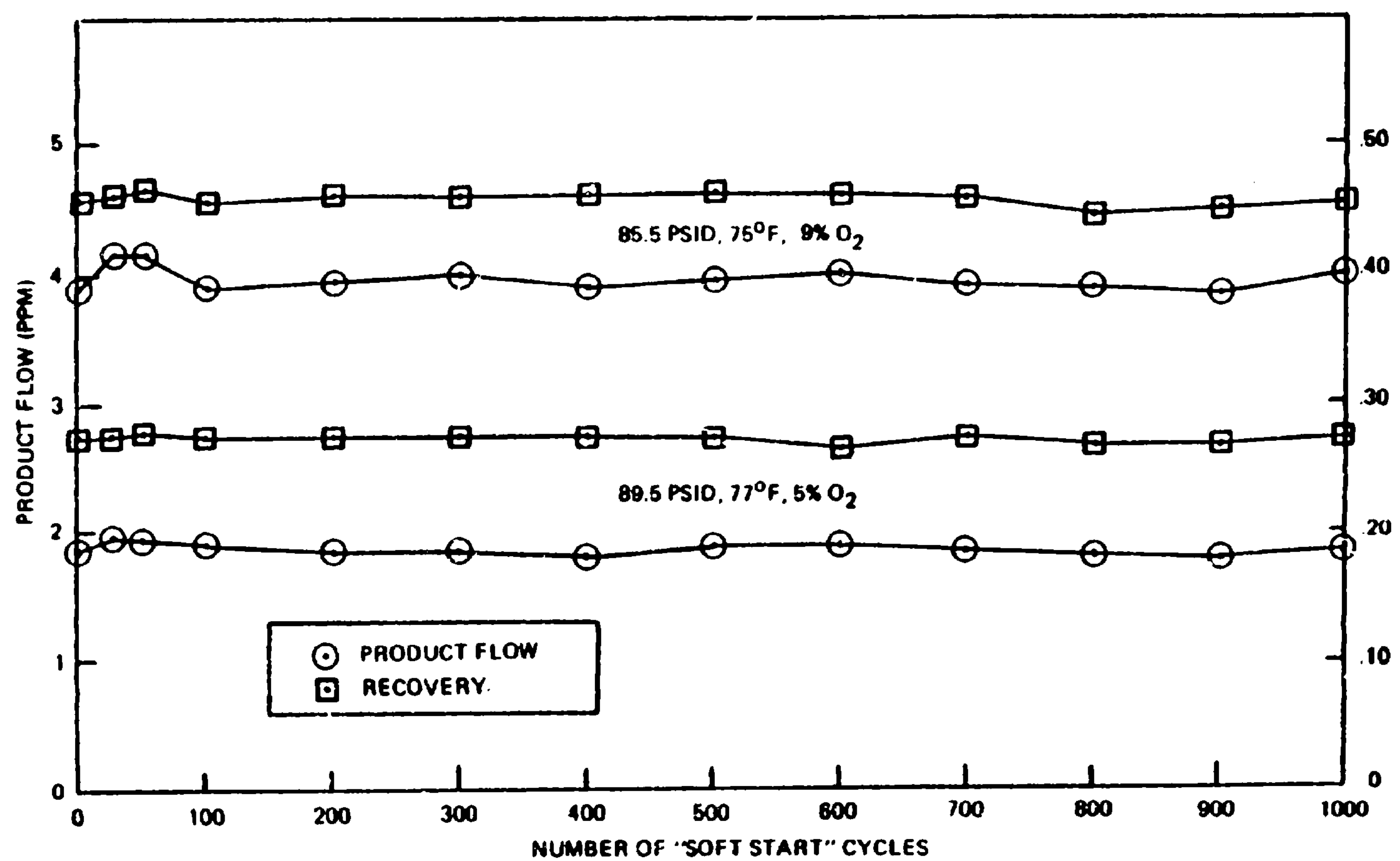


Figure 32. "New" PMIGG Performance VS "Soft Start" On – Off Cycles

5.3 MSIGG/KC-135 Mission Simulation Results

This section describes the performance of the MSIGG in the simulated KC-135 mission in terms of meeting the requirements for keeping the tank ullage inert.

5.3.1 Mission Profiles Tested

Due to a limitation of the computer data system, it was convenient to limit the mission profile length to less than 300 minutes. The original mission length (see Appendix E) was reduced from 306 minutes to 286 minutes by reducing the cruise portion (between 240 and 260 minutes). (The cruise portion of the flight presents a steady state condition; therefore, this reduction should not affect the test results). This 286 minute mission was labeled KC-135 Mission A. A second mission, labeled KC-135 Mission B with a duration of 293.3 minutes, was also used to simulate a slower descent rate. These missions are compared graphically in Figure 33.

5.3.2 Results with Baseline 286 Minute KC-135 Mission A

The results of the 286-minute KC-135 Mission A simulation are presented in Figure 34 (more detailed data are available in Appendix H) and indicate that the ullage oxygen concentration dropped below 9% within 25 minutes and stayed below 9% for the balance of the mission. However, surge tank pressure dropped below ambient and MSIGG product oxygen concentration rose above 9% during two descents near the end of the mission. Since these conditions were not consistent with the criteria in Section 1.2, three changes were made to improve MSIGG performance:

- o The MSIGG regulator inlet pressure setting was increased for the high flow descent mode. Steady state performance data indicated that the pressure regulator setting should be increased from 35.5 psig to 42 psig in order to maintain the oxygen concentration below 9%.

- o In order to get the MSIGG into high flow mode as soon as possible, the descent switch setting was changed to command high flow below 2.0 psig tank pressure rather than the 0 psig setting selected by the

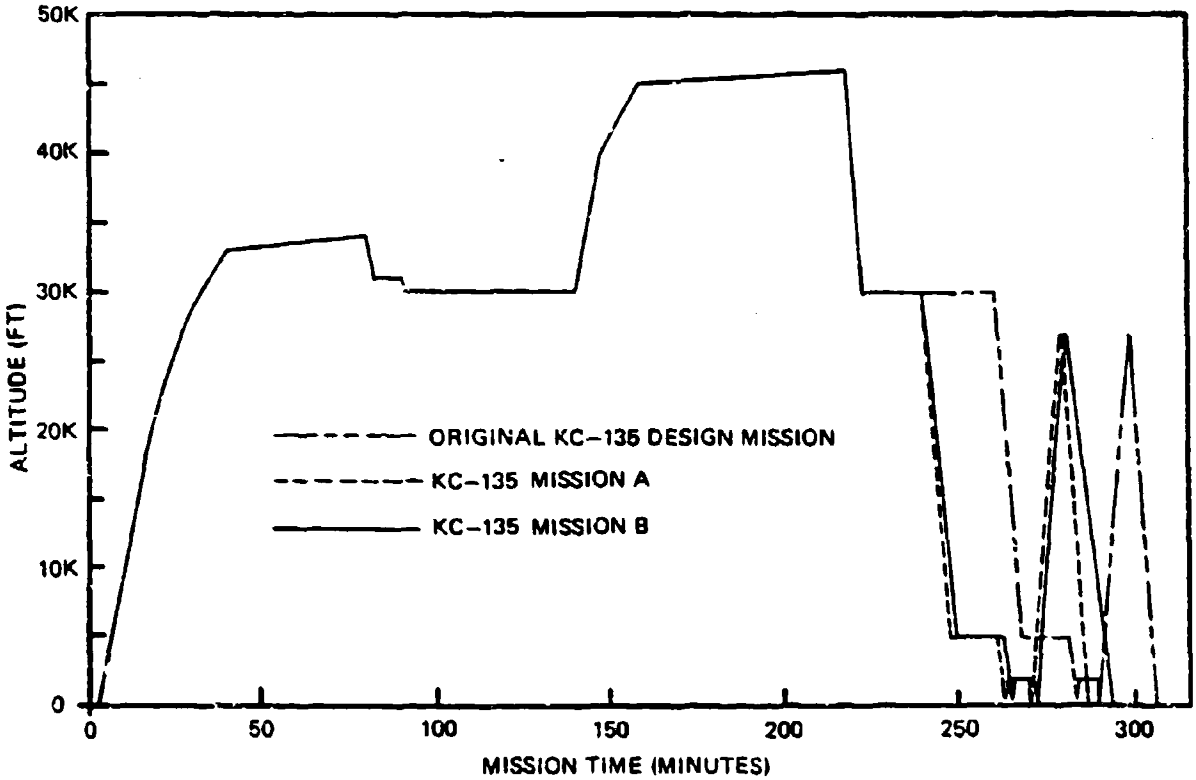


Figure 33. Mission Profiles

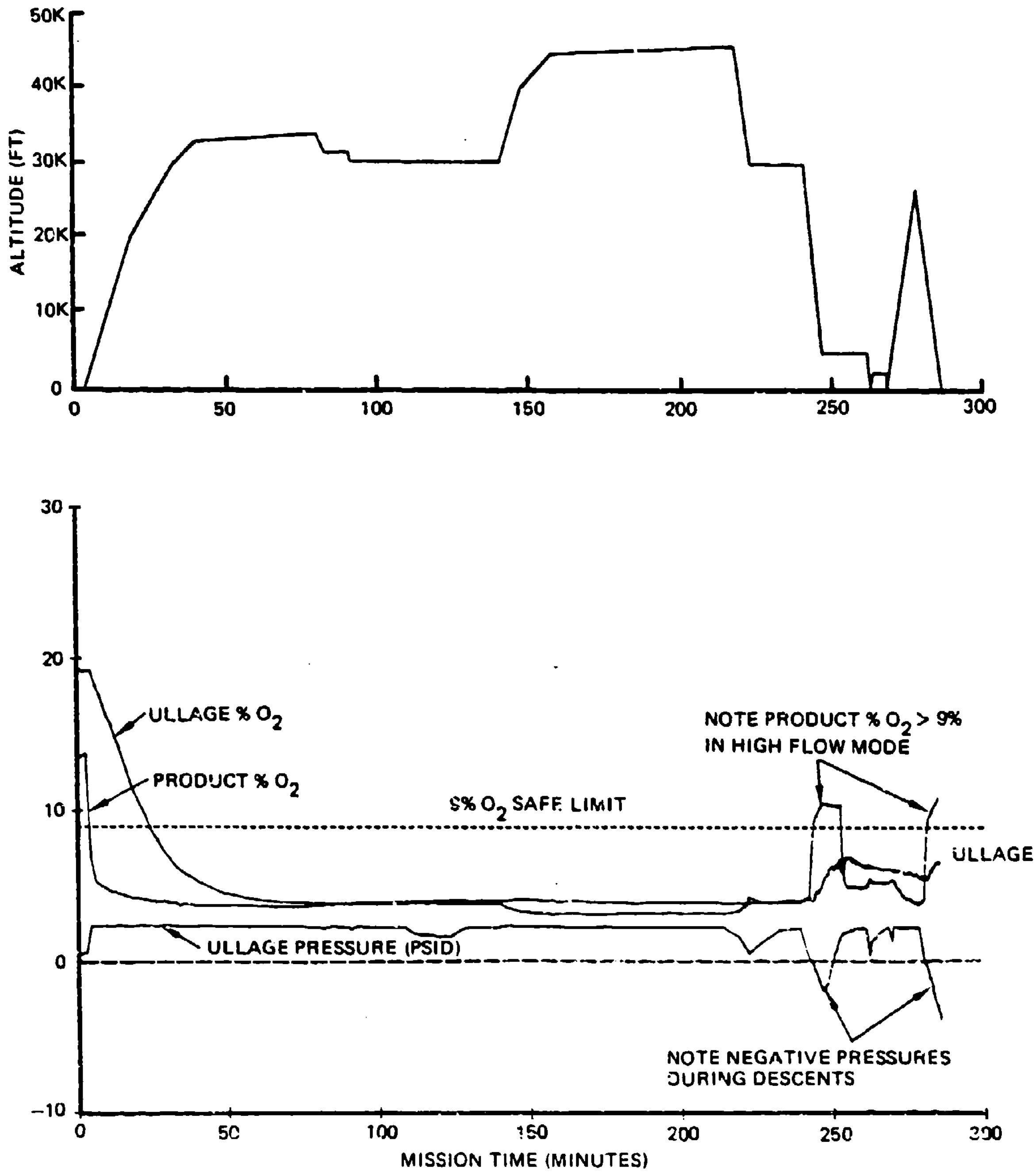


Figure 34. MSIGG/KC−135 Mission A Results

manufacturer. This change allowed more time for the MSIGG to provide the make-up gas required during descent (i.e. get into "high gear" as soon as possible).

- The mission was also changed to the slower descent rate KC-135 Mission B profile to reduce the repressurization flow requirements.

5.3.3 Results with Amended 293.3 Minute KC-135 Mission B

The essential KC-135 Mission B simulation results are presented in Figure 35 (more detailed data are presented in Appendix H). Inspection of the data reveals:

- The ullage oxygen concentration time history was similar to that of the KC-135 Mission A. The oxygen concentration dropped below 9% within 25 minutes, stayed at approximatey 4% for most of the mission and then climbed to 6.5% during the final descent. The increase in oxygen content near the end of the mission was due to the entry of IGG product gas which was between 8 - 9% oxygen in high flow mode.

- The change made in the bleed air inlet regulator setting (35.5 to 42 psig) successfully maintained the product oxygen concentration below 9%. Product oxygen concentration was between 3 - 4% for most of the mission and remained less than 9% during the final descent.

- The surge tank pressure remained positive throughout the entire mission (minimum of +0.5 psid) as a result of the changes to the descent switch setting and the slower descent rates.

5.3.4 Discussion of Results

The results of this KC-135 Mission B simulation show that the MSIGG performance met the criteria in Section 1.2. The changes to the descent switch and inlet regulator settings can be viewed as control system adjustments that were necessary for the MSIGG to meet performance goals. A production MSIGG could benefit from a similar but more detailed inlet pressure regulator control scheme. In the test program, increasing the regulator

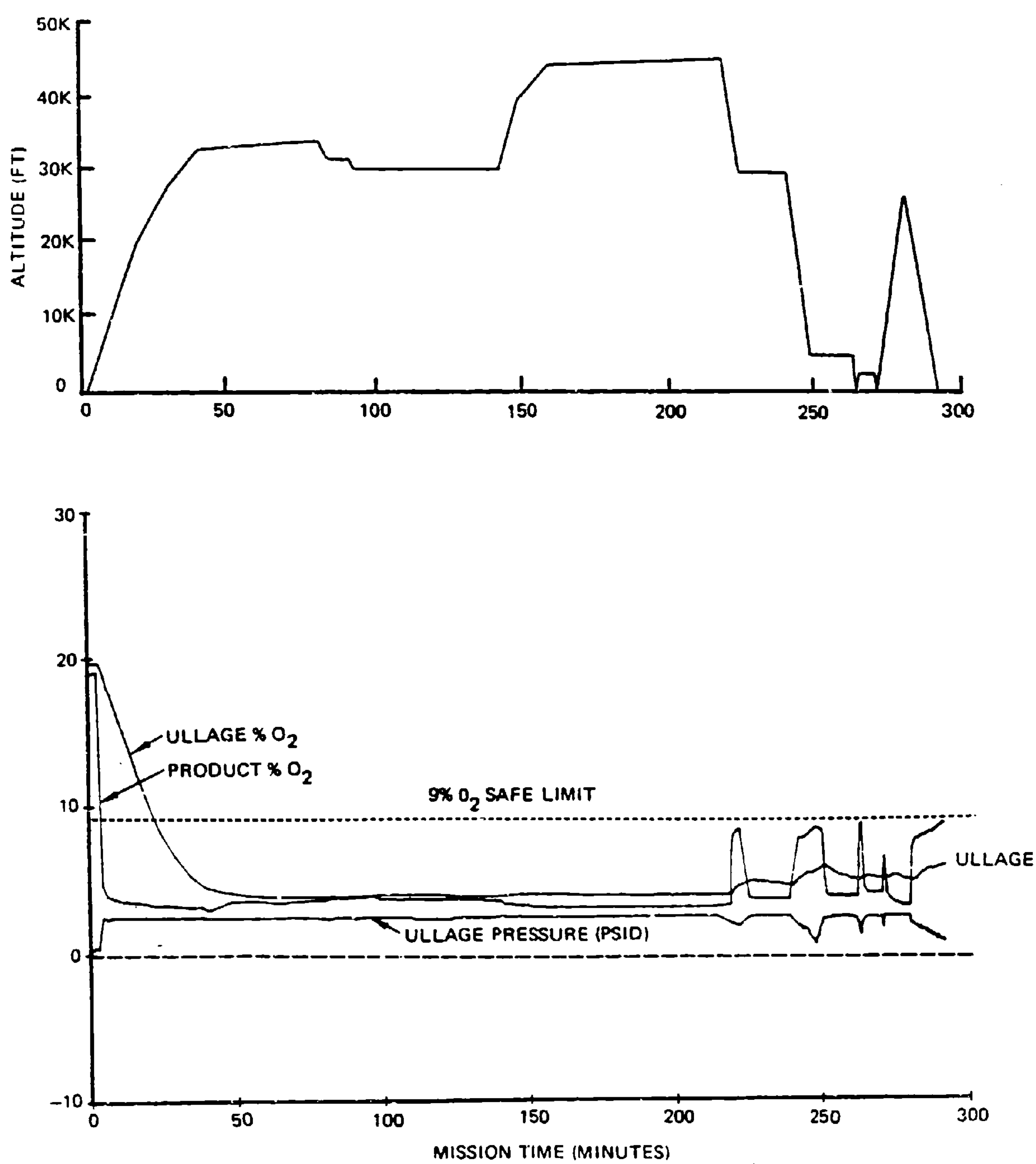


Figure 35. MSIGG/KC−135 Mission B Results

setting for the high flow mode had the same effect on the low flow mode due to the simplicity of the regulator control scheme. This control scheme resulted in higher bleed air usage than was necessary in the low flow mode.

The product flow rates generated by the MSIGG in these tests were significantly less than actual descent requirements. While the simulator mission could be modified by reducing the descent rate, the same could not be done on an airplane; in fact the airplane should be protected during the much higher rate emergency descent. Likewise, for cold day operations where more product mass is required to pressurize the ullage, a larger MSIGG unit is indicated. These observations suggest that a stored gas NEA system would be a better solution than a demand system for fuel tank inerting application. A stored gas NEA system would include high pressure bottles charged by compact compressors coupled to an IGG. The IGG would be sized to provide both the proper climb scrub flow rate and bottle pressurization rate, such that the stored system could then accommodate any descent rate. This approach may have distinct advantages for fighter airplane inerting, where the descent rates are higher than in typical cargo and tanker fleets.

5.4 PMIGG/KC-135 Mission Simulation Results

5.4.1 Mission Profiles Tested

The same profiles used for the MSIGG were also used for the PMIGG. See Section 5.3.1 for a discussion of these missions. Other mission details are available in Appendix E.

5.4.2 Results with Baseline 286-Minute KC-135 Mission A

The results of the baseline 286-minute KC Mission A simulation are presented in Figure 36 (more detailed data are presented in Appendix I). Note that the ullage oxygen concentration dropped below 9% within 27 minutes and stayed below 9%, as desired. However, a negative surge tank pressure occurred once and a product oxygen concentration above 9% occurred three times during the mission. This situation was unacceptable performance based upon the criteria in Section 1.2. In order to improve performance, changes were made to the PMIGG test procedure as follows:

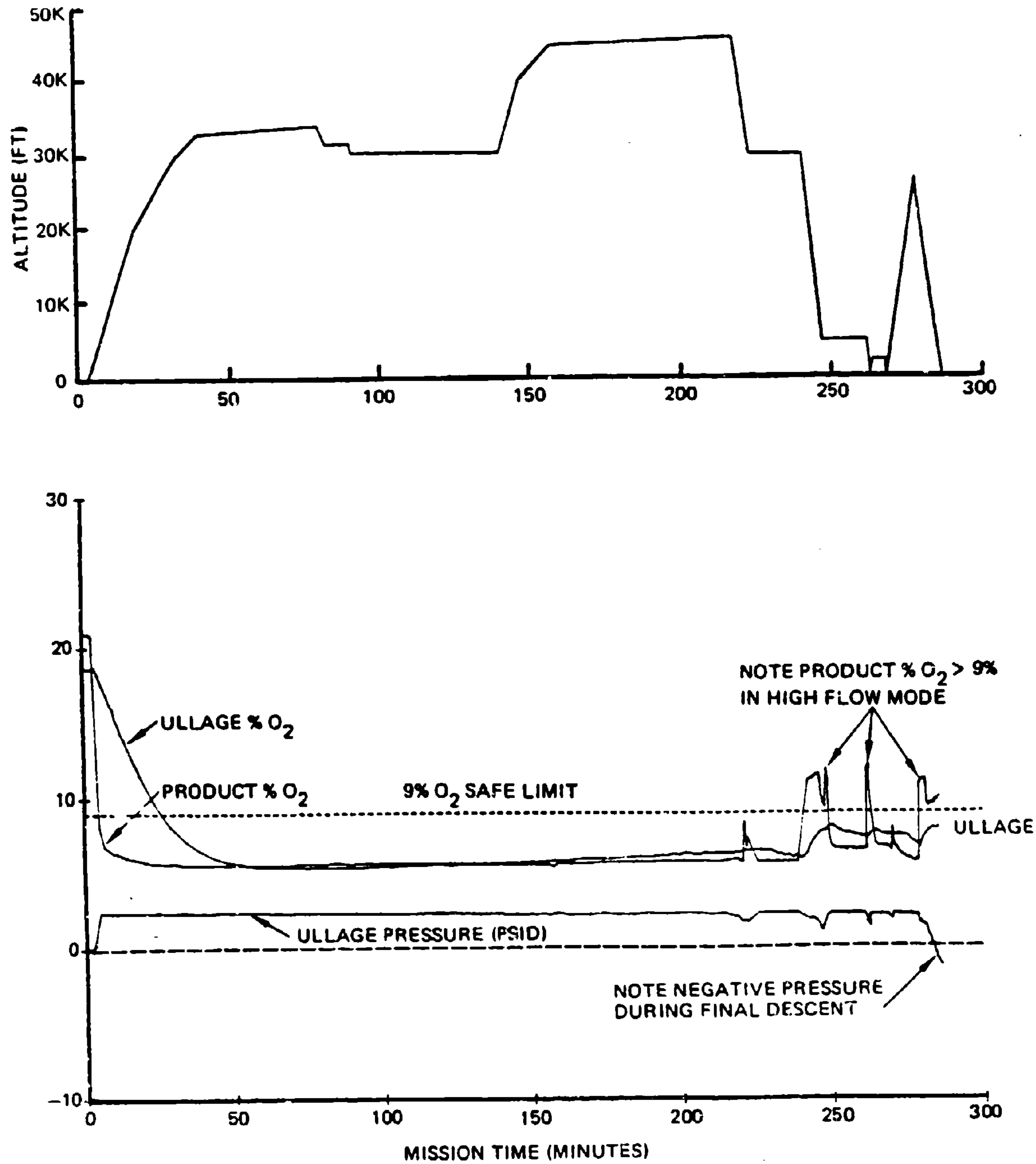


Figure 36. PMIGG/KC–135 Mission A Results

- The simulated descent rates were decreased (i.e. slower descent rates) to allow more time for the PMIGG to provide the required re-pressurization make-up gas. This change was accommodated with the KC-135 Mission profile.

- The control for switching the PMIGG into the high pressure/high flow mode was changed from a fuel system pressure sensor to a product gas flow sensor, in-line with the demand regulator. Whenever demand flow was sensed, scrub flow was turned off; thus the demand regulator opened sooner (scrub flow delayed demand regulator full opening until well into descent).

- The maximum flow rate through the demand regulator was reduced slightly to assure that the PMIGG product oxygen concentration did not climb above 9% in high flow mode.

5.4.3 Results with Amended 293.3 Minute KC-135 Mission B

The KC-135 Mission B simulation was performed with the changes described above and the results are presented in Figure 37 (more detailed data are presented in Appendix I). The following is a list of observations from inspection of data:

- The ullage oxygen concentrations were similar to those of the KC-135 Mission A. The ullage oxygen concentration dropped below 9% within 27 minutes, stayed below 6% for most of the mission and then climbed to as high as 7.5% during the final descent. The increase in the ullage oxygen concentration during descents is due to the entry of IGG product gas which was near 9% oxygen in high flow mode.

- The surge tank pressure remained positive throughout the entire mission (minimum of +.65 psid) as a result of the changes to the high flow control scheme and slower descents.

- The PMIGG product oxygen concentration was maintained essentially below 9% (the concentration actually increased to 9.2% twice during the mission for short periods of time).

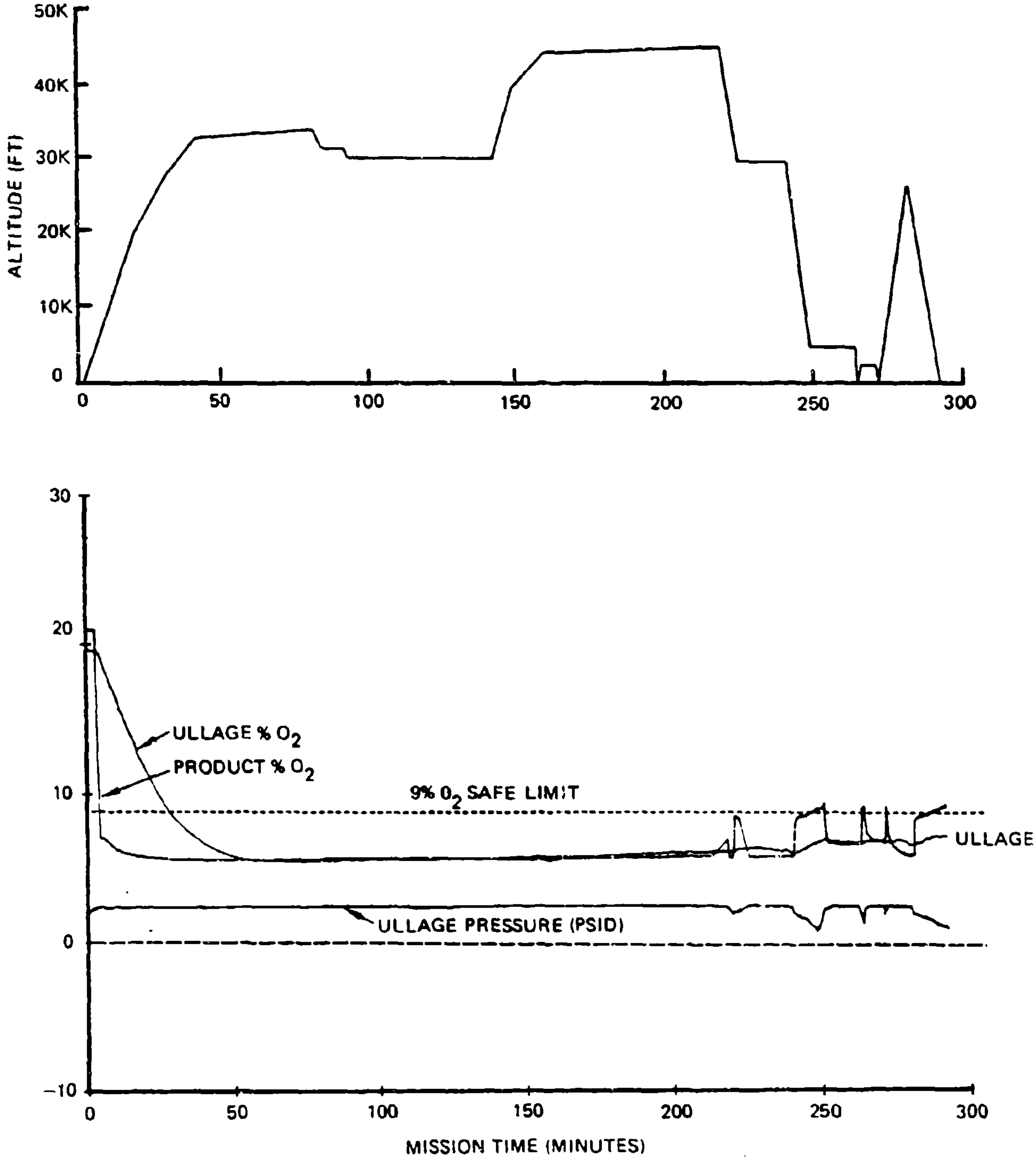


Figure 37. PMIGG/KC–135 Mission B Results

5.4.4 Discussion of Results

The results of the KC-135 Mission B simulation show that the PMIGG performance met the criteria in Section 1.2. The changes to the high flow/high pressure mode control (changed from a descent switch to a demand flow sensing switch) can be viewed as a control system refinement necessary for the PMIGG to meet performance goals. A simpler and probably more reliable control system to regulate PMIGG operation would be one similar to that used by the MSIGG: a single fuel system pressure switch which turns "off" scrub flow and goes to high flow mode as soon as the fuel system pressure drops below a specified level.

The PMIGG manufacturer has underestimated the descent flow requirements, since the descent rates had to be decreased to maintain a positive fuel system pressure. In addition, the KC-135 mission used here is not necessarily the most severe case from a descent standpoint. This problem points out a need to develop an IGG system which is not flow rate limited, such as a stored gas system. Such a system would store enough NEA in high pressure bottles to repressurize the maximum ullage volume during a descent regardless of the rate of descent.

6.0 DATA ANALYSIS AND COMPARISONS

6.1 Comparison of MSIGG and PMIGG Performance

As discussed earlier, a number of variables affect IGG product flowrate and quality including inlet pressure, bed temperature, and waste stream pressure. It is useful to compare the performance of the two IGG units for the same operating conditions to assess the relative airplane penalties and sensitivities to adverse operating environments. For comparison purposes to the MSIGG, flow rates have been doubled for the PMIGG since a half size unit was tested.

6.1.1 Inlet Flow and Pressure Requirements

The inlet flow rate required to produce a given product flow rate and quality is an important performance characterisitc; the PMIGG ASM, while operating at a higher pressure, requires substantially less inlet air than the MSIGG due to its higher recovery. The lower inlet air requirement for the PMIGG is illustrated in the comparison plot of Figure 38. The PMIGG has a higher recovery factor or efficiency than the MSIGG by a factor of nearly 2. However, the high pressure (75-85 psig) and constant 75^{o}F requirements of the PMIGG impose a bleed-air penalty for the KC-135 by making a turbo-compressor based ACM necessary to condition the bleed air. The MSIGG, on the other hand, operates with normal KC-135 bleed air pressures. Thus, the total PMIGG system flow requirement is signficantly higher than that of the MSIGG. This effective PMIGG bleed air requirement for the KC-135 is shown in the upper area of Figure 38 and indicates that for a 5% product at 3 PPM the bleed air flow must increase by approximately a factor of 4 (from 13 to 52 PPM) due to the ACM penalty, with a decrease in recovery factor from 0.24 to 0.06 (compared to 0.13 for the MSIGG). A similar trend can be seen at 8 PPM.

6.1.2 Inlet Air Temperature Sensitivity

The effect of inlet air temperature on the performance of the PMIGG and MSIGG ASM's is shown in Figure 39. Note that increasing the inlet air temperature has opposite effects on the product quality of the two units: the product quality improves with the PMIGG and degrades with the MSIGG. Note that both units require more inlet air as temperature is increased (i.e. they become less efficient).

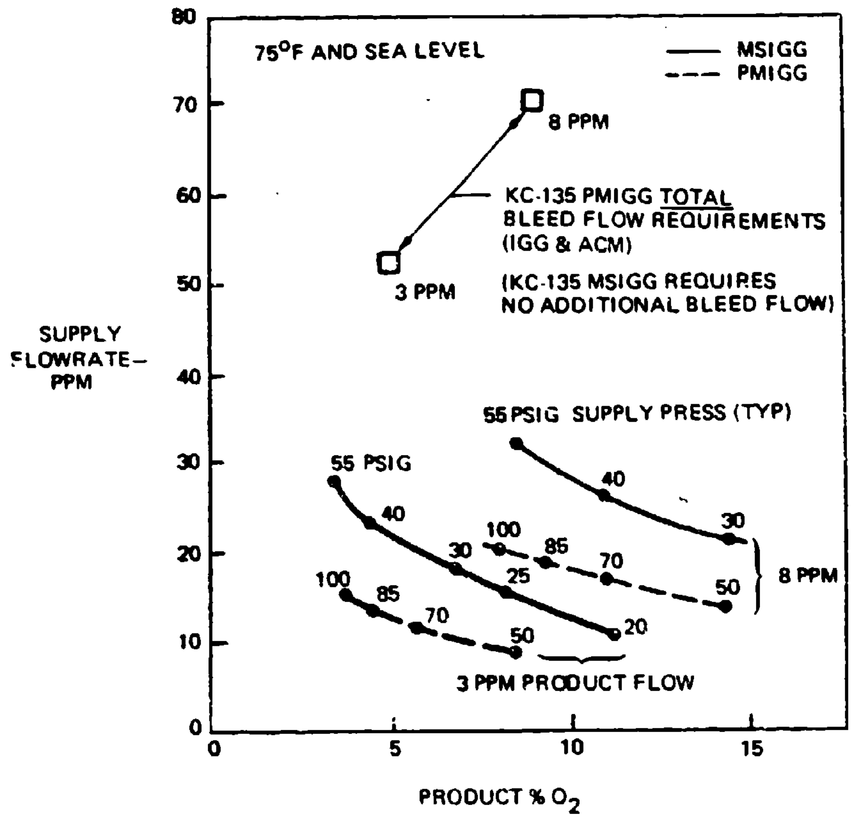


Figure 38. Comparison of MSIGG and PMIGG Supply Flow Requirements

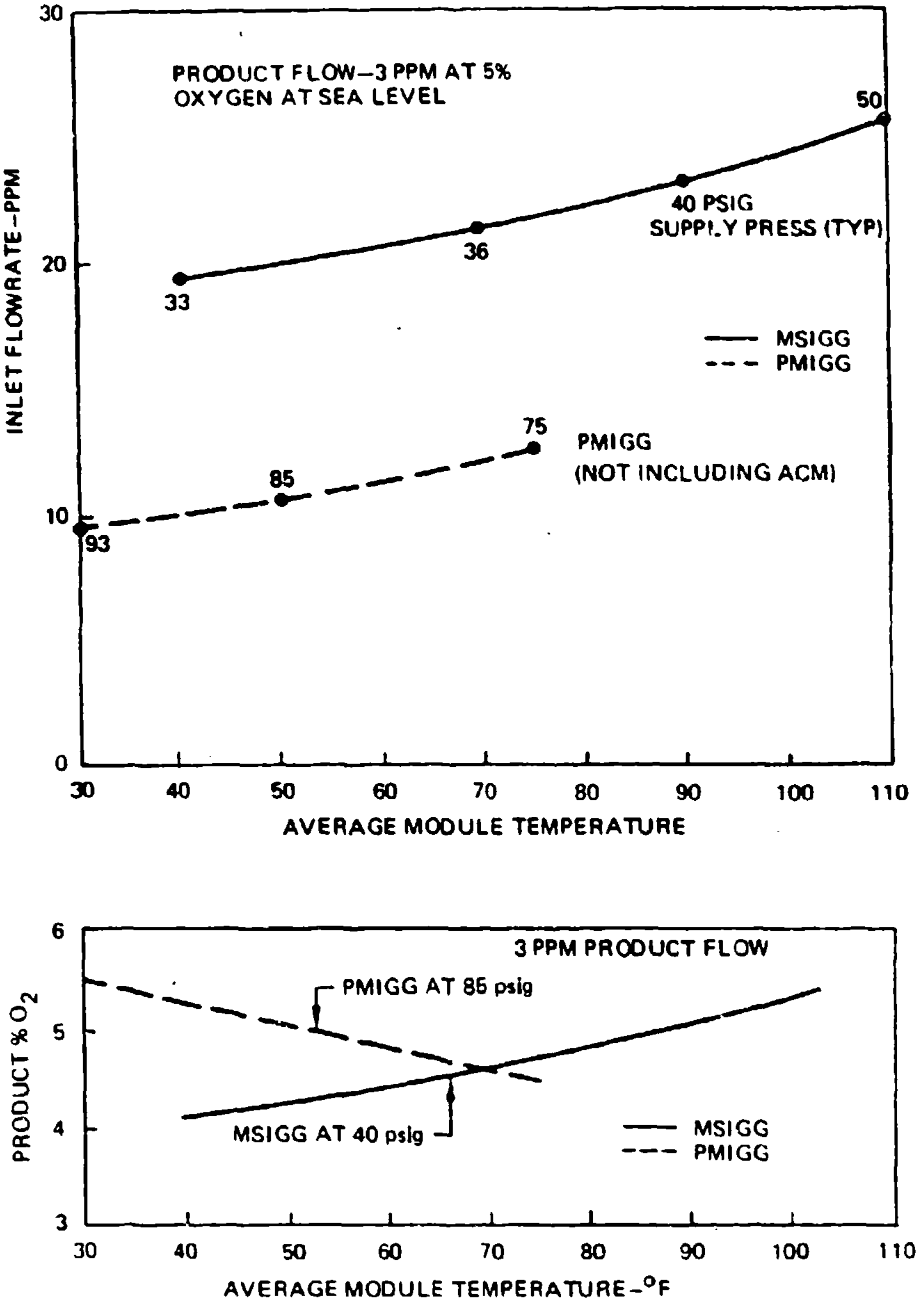


Figure 39. Comparison of MSIGG and PMIGG Temperature Sensitivity

The PMIGG manufacturer recommended a 75°F operating temperature as the best tradeoff between performance and fiber lifetime (Reference 1 indicates fiber life is shortened at higher temperatures). The MSIGG can be operated over a wide temperature range without any permanent effect on performance.

6.1.3 Altitude Sensitivity

As indicated in Figure 40, the MSIGG showed a significantly greater performance improvement at altitude than did the PMIGG. This means that at altitude, the operating pressure of the MSIGG can be reduced while still maintaining the same product quality. However, for all practical purposes, the PMIGG's performance can be considered to be unaffected by altitude. The PMIGG would require the same operating pressure regardless of altitude.

6.2 OBIGGS KC-135 INSTALLATION WEIGHT AND PENALTY COMPARISON

The results of a study comparing the weights and fuel penalties of a PMIGG and MSIGG OBIGGS installed in a KC-135 are shown in Table 7. Although the MSIGG has a larger fuel penalty due to a greater system weight than the PMIGG, the lower ram cooling air and engine bleed air requirements of the MSIGG result in a total fuel penalty less than that of the PMIGG. The airplane range loss or equivalent payload differences associated with each system are not great, however. Final choice would depend upon the lifetime of the air separation material and the reliabilty of the associated equipment, e.g. the air cycle machine of the PMIGG and the sequencing valves of the MSIGG. These factors were not definitively evaluated in this test program. The originally planned PMIGG air cycle machine was not built and tested as a unit. The MSIGG sequencing valve system that experienced early failures was not representative of flight hardware, but was assembled from industrial components and simple valve designs primarily to demonstrate the air separation performance of the large multiple bed MSIGG concept.

6.3 DESCENT REQUIREMENTS

The most significant problem encountered during the KC-135 mission simulations was the inability of either the PMIGG or the MSIGG to maintain positive tank pressures during descents. This deficiency is due to the underestimation of descent requirements by the IGG manufacturers. The following discussion will analyze how descent makeup requirements should be estimated and the reason for the underestimates.

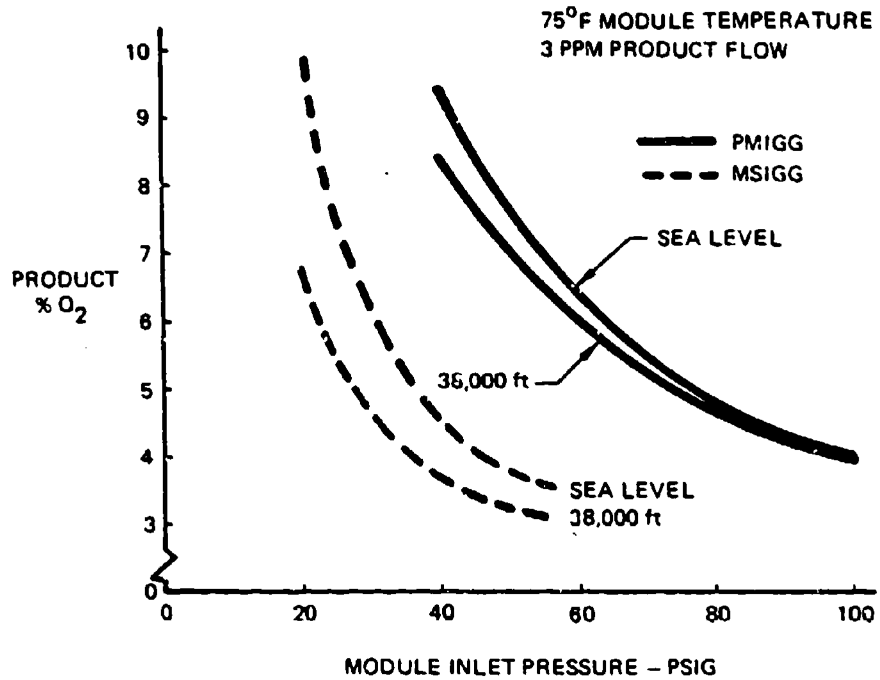


Figure 40. Comparison of MSIGG and PMIGG Altitude Sensitivity

Table 7. KC-135 PMIGG and MSIGG Weight and Fuel Penalty Comparison

5.1 hour design mission — 8 PPM at 9% O_2 OBIGGS

PMIGG

[1] Weight

- Air separation module
  - Fiber bundles — 280 lbs
  - Wrap-up — 140 lbs
- Air cycle machine — 87 lbs
- Valves and controls — 35 lbs
- Pre-coo' ducts and plumbing — 170 lbs

Total — 712 lbs

[2] Weight fuel penalty =

$$\left(712\ \text{lbs}\right)\left(.0369\ \frac{\text{PPH fuel}}{\text{lb weight}}\right)\left(5.1\ \text{hrs}\right) = 134\ \text{lbs}$$

Ram cooling air

- Precooler — 52 PPM avg
- ACM heat exchanger — 42 PPM avg

Total — 94 PPM

[2] Ram air fuel penalty =

$$\left(94\ \text{PPM}\right)\left(.00817\ \frac{\text{PPM fuel}}{\text{PPM ram air}}\right)\left(306\ \text{min}\right) = 235\ \text{lbs}$$

Bleed air — 47 PPM avg

[3] Bleed air fuel penalty =

$$\left(47\ \text{PPM}\right)\left(.01066\ \frac{\text{PPM fuel}}{\text{PPM bleed air}}\right)\left(306\ \text{min}\right) = 153\ \text{lbs}$$

Total fuel penalty = 522 lbs

[4] Average cruise range loss at 30 Kft = 22 nmi
Average cruise range loss at 45 Kft = 32 nmi

MSIGG

[1] Weight

- Air separation module
  - Sieve material — 382 lbs
  - Wrap-up — 180 lbs
- ECS HX and control — 30 lbs
- Valves and controls — 35 lbs
- Pre-cooler, ducts and plumbing — 170 lbs

Total — 787 lbs

[2] Weight fuel penalty = (787)(.0369)(5.1) = 148 lbs

Ram cooling air

- Precooler — 52 PPM avg
- ECS heat exchanger — 23 PPM avg

Total — 75 PPM

[2] Ram air fuel penalty = (75)(.00817)(306) = 187 lbs

Bleed air — 23 PPM avg

[3] Bleed air fuel penalty = (23)(.01066)(306) = 75 lbs

Total fuel penalty = 410 lbs

[4] Average cruise range loss at 30 Kft = 17 nmi
Average cruise range loss at 45 Kft = 25 nmi

[1] Weight data from manufacturers (references 1 and 2) and BMAC engineering estimates

[2] Weight and ram air fuel penalties from BMAC Wichita performance staff

[3] Bleed air fuel penalty from P&WA J-57-P-59W specification performance curves

[4] Cruise fuel consumption from design mission data (reference 3)

The descent problem can be defined as follows:

Start of Descent	End of Descent
P_1, $V_{1_{@t_1}}$, T_1, R_1	P_2, $V_{2_{@t_2}}$, T_2, R_2

where: P = ullage pressure, Lb/Ft^2 Absolute
V = ullage volume, Ft^3
T = ullage temperature, ^oR
R = ullage gas constant, 53.5 for air
t = mission time, minutes
Subscript 1 denotes conditions at start of descent
Subscript 2 denotes conditions at end of descent

The mass of ullage gas is given by:

$$m = PV/RT$$

To calculate the descent requirements, the difference between m_1 and m_2 must be known.

$$\delta = m_2 - m_1 = (P_2V_2/R_2T_2) - (P_1V_1/R_1T_1) \qquad (1)$$

The above equation will yield the mass of makeup gas required during descent. Equation (1) can be simplified with the following approximations:

$R_1 = R_2 = 54.5$ (@7% O_2 and no hydrocarbons)
$V_1 = V_2$ (no significant fuel usage during descent)
$T_1 = T_2$ (near isothermal compression)

Yielding:

$$\delta m_{simplified} = (P_2 - P_1)V/(54.5T) \qquad (2)$$

The average flowrate of makeup gas required is given by:

$$W = \delta m/\delta t \qquad \text{where } \delta t = t_2 - t_1 \tag{3}$$

The procedure for calculating descent requirements is demonstrated with a specific case of the final descent of the KC-135 Mission A.

Start of Descent

P_1 = 5.0 psia + 2.45 psig tank pressure = 7.45 psia
= 1,072.8 Lb/Ft^2

V_1 = 17,625 Gal Tank Volume -1250 Gal Fuel Remaining
= 2,189 Ft^3

*T_1 = 509^oR

R_1 = 54.7 @ 5% O_2

t_1 = 278.3 Minutes

End of Descent

P_2 = 14.7 psia + 0 psig tank pressure
= 2,116.8 Lb/Ft^2

V_2 = 17,625 Ga - 1150 Gal = 2,202 Ft^3

*T_2 = 525^oR

R_2 = 54.5 @ 7% O_2

t_2 = 286.0 Minutes

*Denotes ullage temperatures from actual mission data.

Substituting these values into equation (1) and (3) yields:

δm = 162.9 - 84.3 = 78.6 Lbs of makeup gas

and

W = 78.6/(286 - 278.3) = 10.2 PPM average flowrate

The IGG unit must supply 78.6 Lbs of NEA into the ullage during the final descent if tank pressure is to remain above ambient.

The sizing requirements for the KC-135 OBIGGS were developed in Reference 1 and indicated 8 PPM were adequate for descent. The reason for the discrepancy was assumptions made regarding ullage temperature during the descent. Reference 1 predicts that for the standard day mission, the ullage temperature would increase from 450^{O}R to 570^{O}R while actual mission simulation data shows only a 16^{O}R rise. The Reference 1 analysis was evidently based on a near adiabatic compression of the ullage gas while the simulation indicated that near isothermal is actually the case. A discussion of this compression process is given in Appendix J.

When sizing an OBIGGS for an application such as the one discussed here, the following considerations will demand even higher IGG flowrates:

- Cold day missions will require approximately 25% higher flows.
- The descent switch will not detect the exact beginning of a descent and probably will not operate until at least 10% of the total time for descent has passed. This delay will leave less time for repressurization.
- A "safety factor" or reserve capacity should be built into the system.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The following conclusions are presented as derived from the extensive tests conducted on the DOW/AiResearch PMIGG and the Clifton Precision MSIGG as well an analysis of KC-135 OBIGGS weights and penalties:

- Both the MSIGG and the PMIGG are capable of inerting a KC-135 fuel system (as well as other airplane fuel systems), providing that the IGG unit is sized to properly handle the descent flow requirements.

- Selection of a PMIGG or MSIGG for a KC-135 application would depend more upon reliability and lifetime factors rather than system weight and fuel penalty differences.

- Both IGG manufacturers (AiResearch and Clifton Precision) underestimated the descent flow requirements for the given KC-135 mission by approximately 40%.

- When calculating descent flow requirements for an airplane fuel system, the repressurization process should be considered to be isothermal or dominated by the tank structure and fuel mass.

- A design margin should be incorporated into an OBIGGS to allow for a predetermined amount of system degradation.

- The MSIGG is subject to a minor, one time performance shift due to moisture in the inlet air. An additional temporary drop in performance occurs during periods of operation under high moisture conditions.

- The 8-bed MSIGG unit, as designed by Clifton Precision, will require improved valves in order to achieve acceptable reliability.

- The PMIGG modules will require special slow opening inlet control valves to prevent fiber bundle damage.

- The PMIGG performance is not significantly affected by moisture in the inlet air.

7.2 Recommended Methodology for Evaluating Future OBIGGS

Several techniques for evaluating OBIGGS performance were developed in this program and should be considered in any future performance/suitability testing, including:

- Basic performance mapping over a minimum of 4 operating points for each of the following parameters - inlet air pressure, product flowrate, waste pressure, and temperature of the IGG unit.

- Long term performance testing over several hundred hours, focusing on one or two important flow and inlet condition points, should be performed.

- Controlled on/off cyclic testing for the normally continuous flow PMIGG type units to evaluate possible fiber creep and other failure/degradation effects. The pressurization cycle rate should be established based on airplane readiness requirements and the manufacturer's recommendations.

- Inlet air moisture testing is required to assess both short term and long term performance effects, especially for the MSIGG type system. Moisture should be introduced at the inlet conditions reasonably expected during airplane use.

- Mission simulation testing should be performed to verify both the basic performance and the control system hardware envisioned for a particular OBIGGS/airplane configuration. The mission simulation should combine the effects of inlet temperature, inlet pressure, and waste pressure while being coupled to a fuel system.

7.3 Areas Requiring Additional Testing

Several factors were not addressed in these tests and should be evaluated in future tests on these and other prototype air separation modules. These include:

- Shock and vibration effects over a long term period should be performed.

- The effect of temperature extremes (i.e. cold soak and hot soak conditions) should be investigated relative to starting time and performance degradation.

- Long term effects of supply air moisture on the MSIGG unit.

8.0 REFERENCES

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4. Lothrigel, A. W., "C-5A Fire Suppression System Instructor Training Guide," Parker-Hannifin Air and Fuel Division, 29 August 1979 Revision.

5. MIL-E-28453A, "General Specification for Environmental Control, Environmental Protection, and Engine Bleed Air Systems," USAF, 1971.

6. "CFM56 - Bleed Air Contamination and Oil Ingestion," Certification Report #CR-036, December 1978.

7. Society of Automotive Engineers, "Environmental Control System Contamination," Aerospace Information Report AR 1539, 30 January 1981.

8. "CFM56 - Dust Ingestion Test, Bleed Air Dust Contamination," Report #79-001, Janaury 1979.

9. "Compressed Gas Handbook," NASA SP-3045, 1969.

9.0 LIST OF TERMS

ACFM	Actual Cubic Feet Per Minute
ACM	Air Cycle Machine
ASM	Air Separation Module
CFM	Cubic Feet Per Minute
IGG	Inert Gas Generator
MSIGG	Molecular Sieve Inert Gas Generator
NEA	Nitrogen Enriched Air
OBIGGS	On Board Inert Gas Generator
PMIGG	Permeable Membrane Inert Gas Generator
PPM	Pounds Per Minute or Parts Per Million
PSA	Pressure Swing Adsorption
PSID	Pound Per Square Inch Differential
PSIG	Pounds Per Square Inch Gage
Recovery	Inert Gas Product to Input Supply Air Ratio
SAFTE	Simulated Aircraft Fuel Tank Environment
SCFM	Standard Cubic Feet Per Minute
sFt^3	Standard Cubic Feet
μ	Micron = 10^{-6} Meters
gr	0.002285 ounces (0.0648 grams)

APPENDIX A

Analysis of IGG Performance Sensitivity to Bleed Air Contaminants

ANALYSIS OBJECTIVE

The objective of this analysis is to assess the performance impact of bleed air contaminants on IGG performance. It would be ideal to evaluate the effects of all possible contaminants over the entire lifetime of an IGG, which will be considered to be 10,000 hours.

TYPES AND SOURCES OF CONTAMINATION

Three types of contamination will be considered; vapor, liquid and particulates.

<u>Sources of Vapor Contamination</u>. These may be any gasses generated from an engine oil leak and the subsequent oil breakdown products. The following is a list of potential substances:

Substance	Allowable Limit as per MIL-E-5007D (PPM)*[1]	Measured in CFM-56 Engine Test (Reference 6)
Carbon Dioxide	5000.0	320
Carbon Monoxide	50.0	37
Ethanol	1000.0	ND*
Fluorine (as HF)	0.1	Not Measured
Hydrogen Peroxide	1.0	0.5
Aviation Fuels	25.0	2.0
Methyl Alcohol	200.0	ND*
Methyl Bromide	20.0	ND*
Nitrogen Oxides	5.0	1.3
Acrolein	0.1	0.7
Oil Breakdown Products	1.0	ND*
Ozone	0.1	ND*
Hydrocarbons (Lube oil, hydraulic fluid, cleaning fluids)	Not Listed	122.0
Glycol	Not Listed	Not Tested

*ND - Non-detected (less than 0.5 PPM)

*[1]PPM - parts per million

The concentrations listed above were measured in a certification test of a CFM-56 engine during a 0.2 GPM (considered severe) oil leak.

Sources of Liquid Droplet Contamination. Liquid droplets can enter the engine compressor from an oil leak caused by faulty seals or servicing, cleaning fluid, and glycol from de-icing. The following is a list of potential substances:

Substance
Engine Lube Oil
Hydraulic Oil
Cleaning Fluids
Glycol

The quantities or concentrations that could be found in bleed air are unknown. Aviation fuels are not listed because it is assumed that fuels will be totally vaporized in the high temperature bleed air. It is possible that liquid droplet contamination, of any kind, does not occur because of vaporization and breakdown in the high temperature air. Data could not be located concerning the presence of liquid droplets in bleed air.

Sources of Particulate Contaminants. These may consist of sand, dust vacuumed off runways, taxi ramps or unimproved fields, and any other airborne particles. Reference 7 discusses the normal particle size distribution encountered in atmospheric dust. Test results from a dust ingestion test of a CFM-56 engine are included in Reference 8.

PROBABILITY OF OCCURRENCE

Of the three types of contaminants, particulates are the most likely to be encountered. The highest concentrations of dust will be encountered during take-off, landing, and ground operation. However, even during flight, small quantities of airborne particles will be encountered. Operation from unimproved runways and desert locations will provide the highest dust levels. Vapor and liquid droplets are assumed to be solely engine generated and not ingested by the engine from atmospheric air. Consequently, vapor and liquid droplet contamination would occur only as infrequent short duration (few hours at the most) transients, usually as a result of some type of engine malfunction such as an oil leak. Combat battle damage could also cause such contamination.

No data is available that predicts the total quantity of vapor or liquid contamination that might be encountered in a bleed air system over the lifetime of an IGG unit.

EFFECTS OF VAPOR AND LIQUID DROPLETS ON IGG PERFORMANCE

Although no test data exists, it is difficult to envision any degradation in IGG performance due to even 122 PPM of hydrocarbons (0.012% by volume), let alone 1 or 2 PPM of the other vapors. However, it is possible that a cumulative long term effect on performance exists. For example, certain molecules may be adsorbed by the MSIGG and not desorbed, causing a gradual accumulation of undesirable substances and a subsequent loss of performance. Likewise, these substances could adversely affect the PMIGG membrane wall material.

An experimental evaluation of these effects (if they exist) would be difficult and extremely time consuming.

EFFECTS OF PARTICULATE CONTAMINANTS ON IGG PERFORMANCE

Both the PMIGG and MSIGG units could be affected by dust accumulating in components such as regulators and valves. However, the major concern is the potential effect on the actual sieve material and membrane bundles.

The sieve material could become coated with dust particles to such an extent that its active surface area available for adsorption is reduced significantly. Also, the dust could cause a greater restriction to gas flow through the bed by "plugging" the spaces between grains of sieve. Both of these effects would tend to occur at the inlet to the bed and would not effect all of the sieve material. In addition, each exhaust cycle will tend to "blow" the dust back out of the beds.

The small holes through membrane fibers of the PMIGG could become "plugged" if internal pressurization were used. The unit under consideration is externally pressurized; therefore, these small holes could not possibly become "plugged." However, the spaces between the millions of parallel fibers could become plugged with dust causing an increased pressure drop and a loss in membrane surface as through the IGG filter.

Entering the Engine Inlet. Reference 8 is a test report of a dust ingestion test on a CFM-56 engine. It is assumed that the dust concentrations used on this test were severe and will be treated as such in this analysis. The dust concentrations are as follows:

Engine Inlet Runway Dust Concentrations and Particle Distribution

	5-15μ	15-25μ	25-50μ	50-100μ	>100μ	
.025 grams/sFt^3 @	20.7%	21.9%	46.6%	7.8%	3%	(Figure A-1)

The above size distribution is by weight and was measured by General Electric to characterize the dust used. The dust, termed "Arizona Road Dust," was supplied by the AC Spark Plug Division of General Motors.

Reference 7 provides data on the particle size distribution and concentrations of atmospheric dust particles. It will be assumed that the aircraft will not operate at close proximity to large cities for any significant amount of time; therefore, the average concentration for non-urban areas (35 micrograms per cubic meter) will be used. Converting units:

Engine Inlet Atmospheric Dust Concentrations

$1. \times 10^{-6}$ grams/sFt^3 at the distribution shown in Figure A-1 and Reference 7

Entering the IGG Filter. This analysis assumes that the IGG uses "raw" bleed air that has not been conditioned by an Environmental Control System. Reference 8 indicates that the dust particles are fractured in the engine compressor and the particle size distribution is shifted (Figure A-1) as follows for high stage bleed:

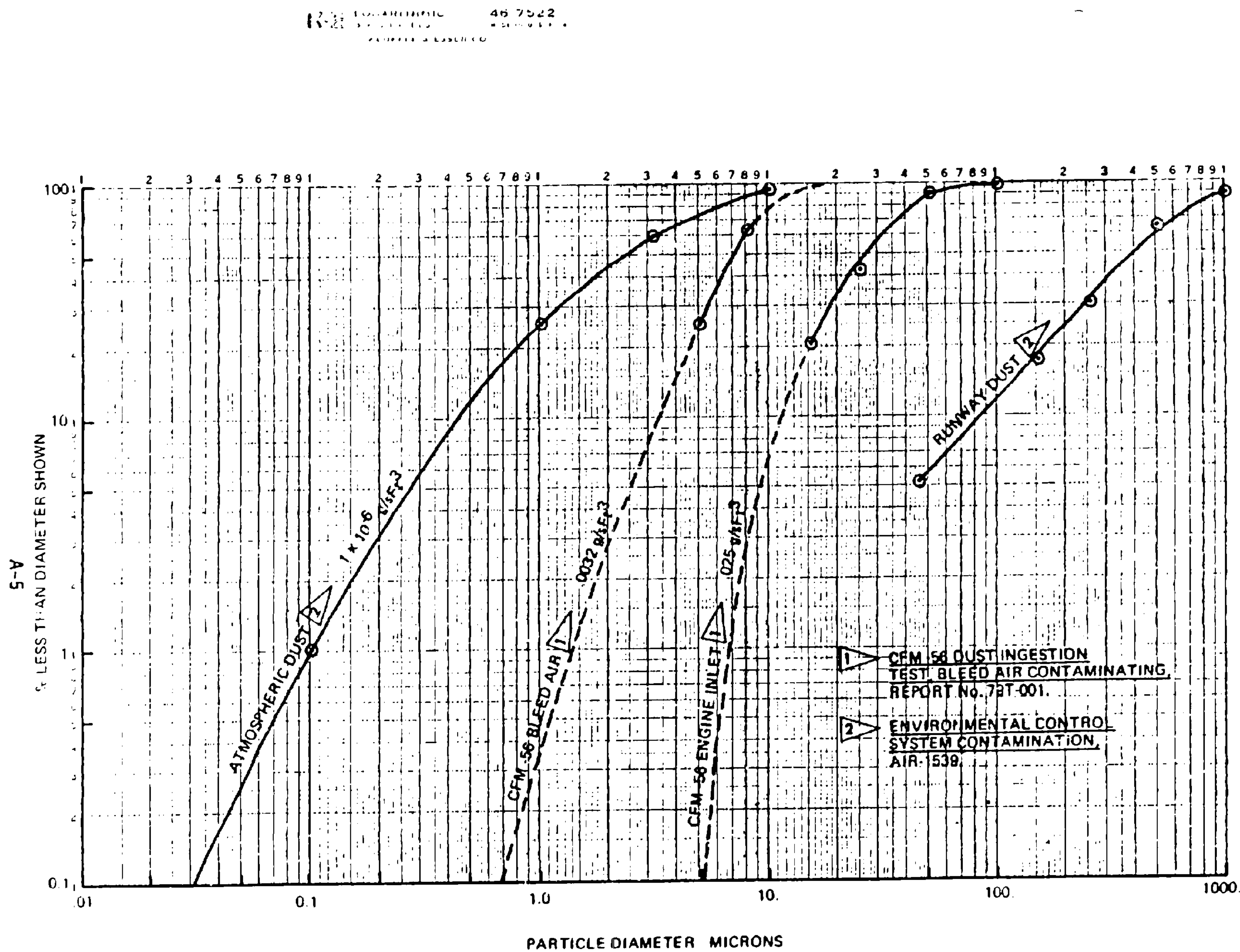


Figure A-1. Dust Particle Size Distribution by Wt.

Engine Shifted Bleed System Runway Dust Concentrations and Particle Distribution

	.4-5μ	5-8μ	>8μ
.0032 grams/sFt^3 @	25%	37.1%	37.9%

The reduction in dust concentration from .025 to .0032 grams/sFt^3 indicates that the engine compressor and bleed port are designed to separate a large portion of the dust. This analysis will assume that .0032 grams/sFt^3 is a severe bleed air dust concentration. Over the lifetime of the IGG, the total quantity of runway dust entering filter is conservatively estimated as follows:

- o 10 Min of dusty operation per take-off
- o One dusty take-off per 25 flight hours (1 out of 5 take-offs)
- o 10,000 hours per IGG lifetime

$$10 \text{ Min } \left(\frac{10{,}000 \text{ hrs}}{25 \text{ hrs}}\right) = 4{,}000 \text{ Min of dusty operation per IGG lifetime}$$

Lifetime Runway Dust Entering Filter

MSIGG	PMIGG
(.0032 g/sFt^3) (280 SCFM) (4,000 Min)	(.0032 g/sFt^3) (160 SCFM) (4,0000 Min)
= 3,584 grams/lifetime	= 2,048 grams/lifetime

Atmospheric dust is much smaller than the "Arizona Road Dust" and poses the question of whether the engine would separate the smaller dust particles at similar efficiencies. To be conservative, it will be assumed that the engine does not separate any of these atmospheric dust particles.

Bleed System Atmospheric Dust Concentrations

$1. \times 10^{-6}$ grams/sFt^3 at the distribution shown in Figure A-1 and Reference 7

Lifetime Atmospheric Dust Entering Filter

MSIGG

$(1. \times 10^{-6}\ g/sFt^3)$ (280 SCFM) (60 Min/Hr) (10,000 Hrs) = 168 grams/lifetime

PMIGG

$(1. \times 10^{-6}\ g/sFt^3)$ (160 SCFM) (60 Min/Hr) (10,000 Hrs) = 96 grams/lifetime

Leaving the IGG Filter. Both the PMIGG and the MSIGG use the same size filter element from the same manufacturer. However, the grades or ratings are not the same and are as follows:

MSIGG	PMIGG
Grade BX	Grade DX
99.99% retention @ .1μ	93% retention @ .1μ

Both grades can be considered to be absolute filters above a few microns.

For runway and atmospheric dust, the filter performance for each IGG will be conservatively estimated as follows:

Runway Dust Leaving Filters

MSIGG	PMIGG
99.99% retention of particles < 5μ	93% retention of particles < 5 μ
100% retention of particles > 5μ	100% retention of particles > 5 μ
Therefore:	Therefore:
(3584 g) (25% < 5μ) (1-.9999)	(2048 g) (25% < 5μ) (1-.93)
= 0.09 grams/lifetime into the sieve beds	= 35.8 grams/lifetime into the membrane canisters

Atmospheric Dust Leaving Filters

MSIGG	PMIGG
99.99% retention of particles < 1μ	93% retention of particles < 1 μ
100% retention of particles > 1μ	100% retention of particles > 1 μ
Therefore:	Therefore:
(168 g) (25% < 1μ) (1-.9999)	(96 g) (25% < 1μ) (1-.93)
= 0.004 grams/lifetime into the sieve beds	= 1.7 grams/lifetime into the membrane canisters

The preceding analysis indicates that an insignificant amount of dust (less than 0.1 gram) would enter the MSIGG beds due to the high efficiency of the filter. The only conceivable way that more dust could enter the beds is as a result of a filter failure or servicing error. Note the analysis is based on a specific type of filter. If the grade of filter is changed by the designer on a later design, then the sensitivity to dust would also change.

For the PMIGG, the preceding analysis indicates that several grams of dust could enter the membrane canisters with the grade of filter chosen. As with the MSIGG, increased amounts of dust could enter the unit as a result of filter failure or servicing error. The amount of dust entering the canisters could easily be reduced by changing to the same grade filter as the MSIGG uses.

APPENDIX B

MSIGG Operating Dynamics

The MSIGG unit consists of eight beds of sieve material manifolded in parallel with each bed containing 50 pounds of zeolite absorbent. Regulated inlet air then enters and exits each of the eight beds through separate inlet and exhaust valves. Each bed is alternately pressurized with inlet air and then exhausted to the waste subsystem in a staggered timing arrangement. A valve timing diagram for the entire MSIGG system is shown in Figure B-1.

During operation of the MSIGG, pressure fluctuations were encountered at the inlet and waste connections when inlet and exhaust valves opened. Fluctuations in pressure and $\%O_2$ are illustrated in Figure B-2. Notice that the regulator outlet pressure (bed inlet pressure) has a periodic fluctuation as a result of alternating pressurization and discharge in each bed. The effect on the product oxygen concentration was seen to be small but measurable. To record meaningful and repeatable data on the computer based data system, a data acquisition routine was developed that would record only the peaks or valleys of the pressures respectively. The peak pressure measured at the inlet would better represent the supply pressure, and the minimum pressure measured at the waste subsystem would better represent the simulated waste pressure.

Since the product oxygen concentrations also fluctuated slightly, the concentration measurement required special treatment in order to be recorded by the computer based data system. This signal to the computer was filtered; thus, computer data fluctuations were less than 0.1 $\%O_2$.

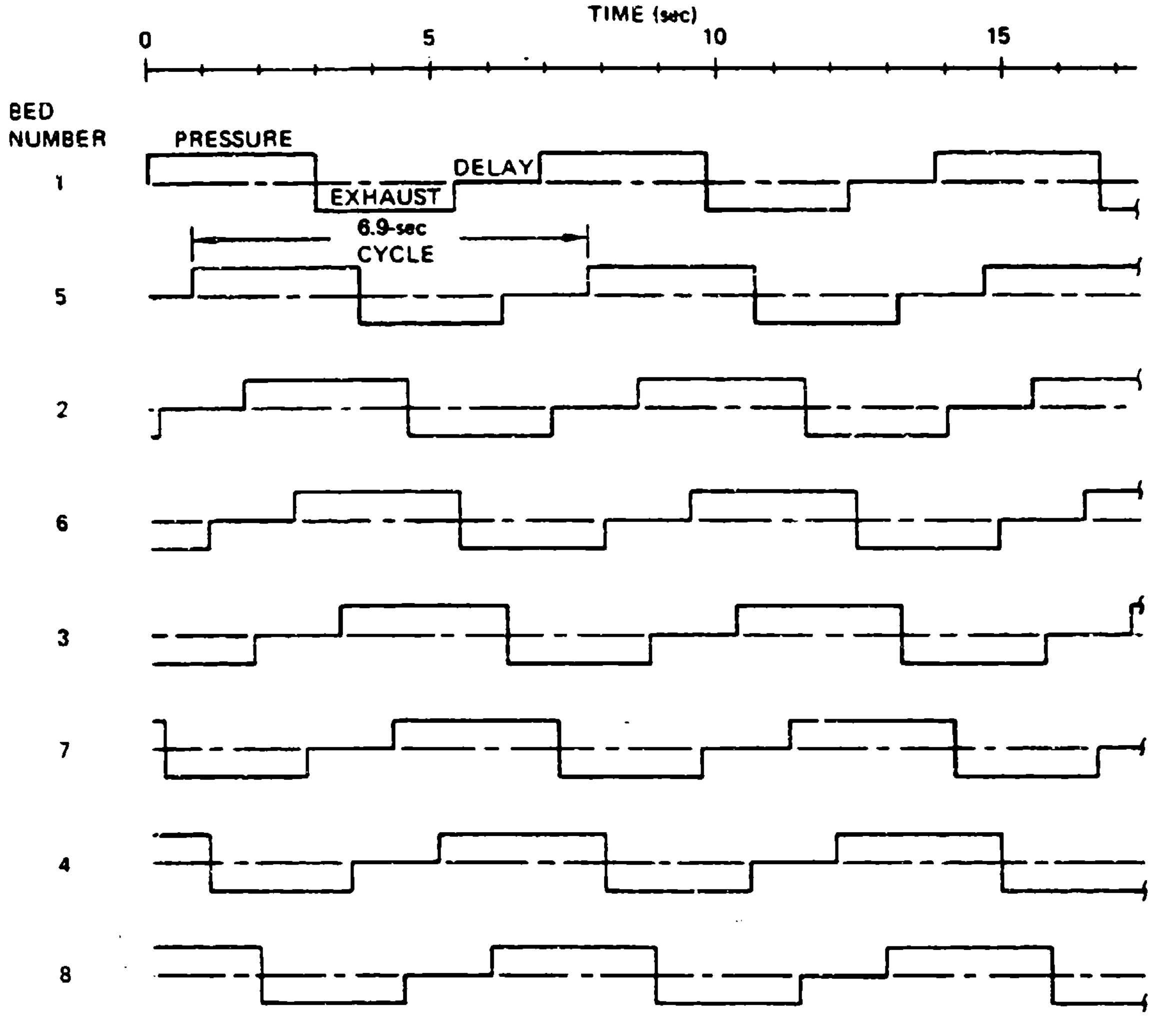


Figure B—1. MSIGG Valve Timing Diagram

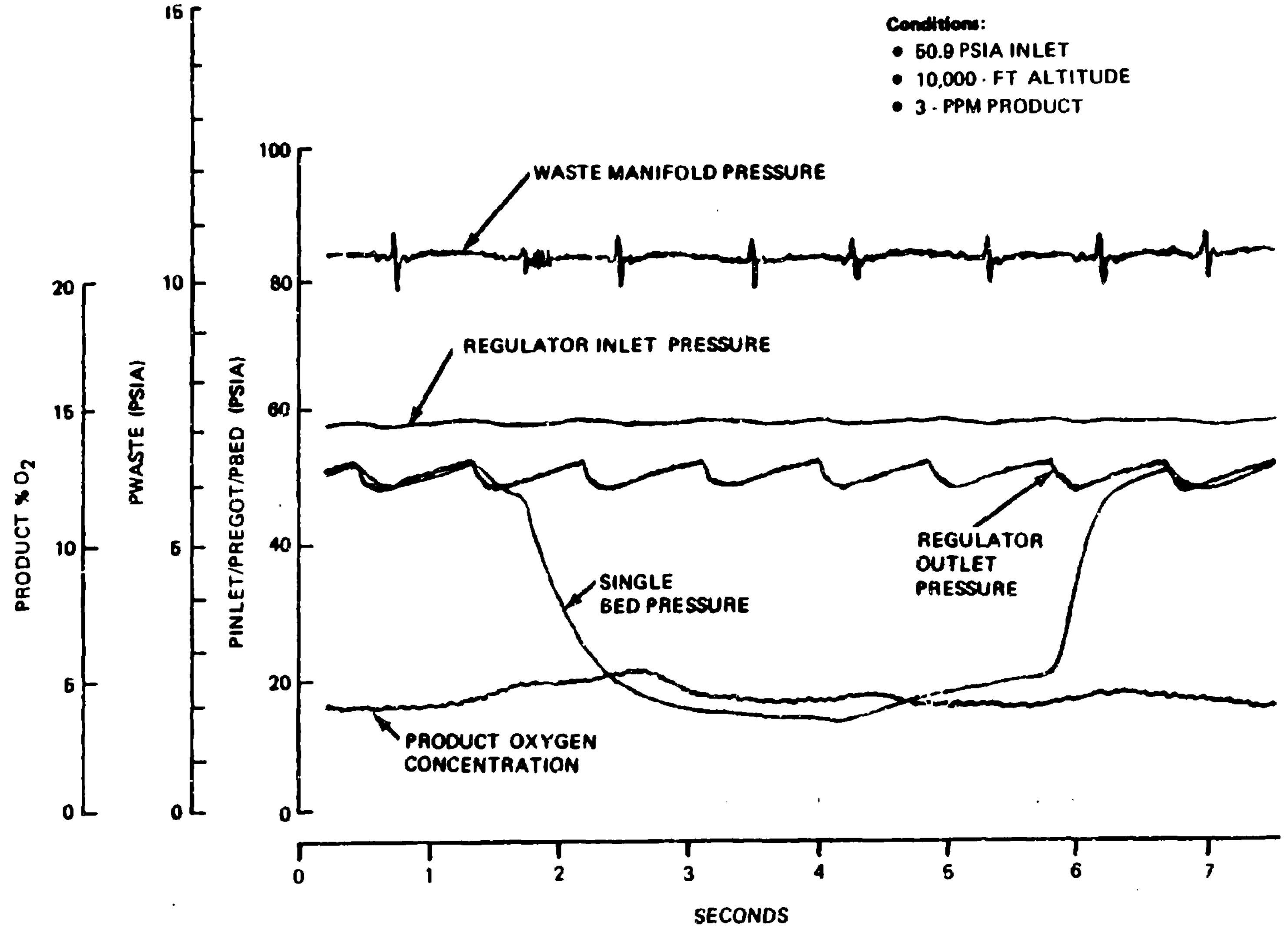


Figure B–2. MSIGG Operating Dynamics

APPENDIX C

Detailed MSIGG Moisture Test Procedures and Results

A detailed schematic of the test setup used for the moisture tests is shown in Figure C-1. Steam was injected into and mixed with the bleed air as the air was heated to the desired IGG inlet temperature. The moist air then passed through the IGG inlet filter/coalescer where droplets of free water were coalesced and drained into a container for measurement of the condensate flow rate. The efficiency of the coalescer was not measured, and it was possible that free water was being re-entrained and then passed into the IGG. After the filter/coalescer, the bleed air passed through the inlet regulator and into the molecular sieve beds. The regulator was set to remain wide open during these tests in order to minimize any pressure drop. However, even in the wide open setting, a 6 psid pressure drop occurred across the regulator at the conditions tested. A dew point meter continuously sampled the regulator outlet air dew point at the regulator outlet pressure; therefore, the dew point of the air entering the beds was always known.

Procedure A (Near Saturation)

In Procedure A increasing amounts of moisture were introduced to the bleed air supply stream under controlled unsaturated conditions (Figure C-2). The moisture content of the bleed air was tested at three different levels (22.8, 62.1, 115.8 grains/lb of dry air) while the bleed air temperature was maintained $10^{O}F$ above the dew point. Initial dry performance was measured, then steam was added to bring the dew point to the desired level, wet performance was measured, the steam turned off, and finally, the dry performance was again checked to assess degradation.

Procedure B (Saturated)

Procedure B was similar to Procedure A except that enough steam was added to the bleed air that the inlet dew point was equal to the inlet temperature. Under these conditions, the bleed air contained free water which coalesced in the IGG inlet filter and drained from the filter housing. Procedure B was only used at inlet air temperatures of $120^{O}F$, resulting in a vapor phase moisture content at the dew point meter of 156.7 grains/lb. The condensate drained from the coalescer filter was collected at a rate of 30 to 40

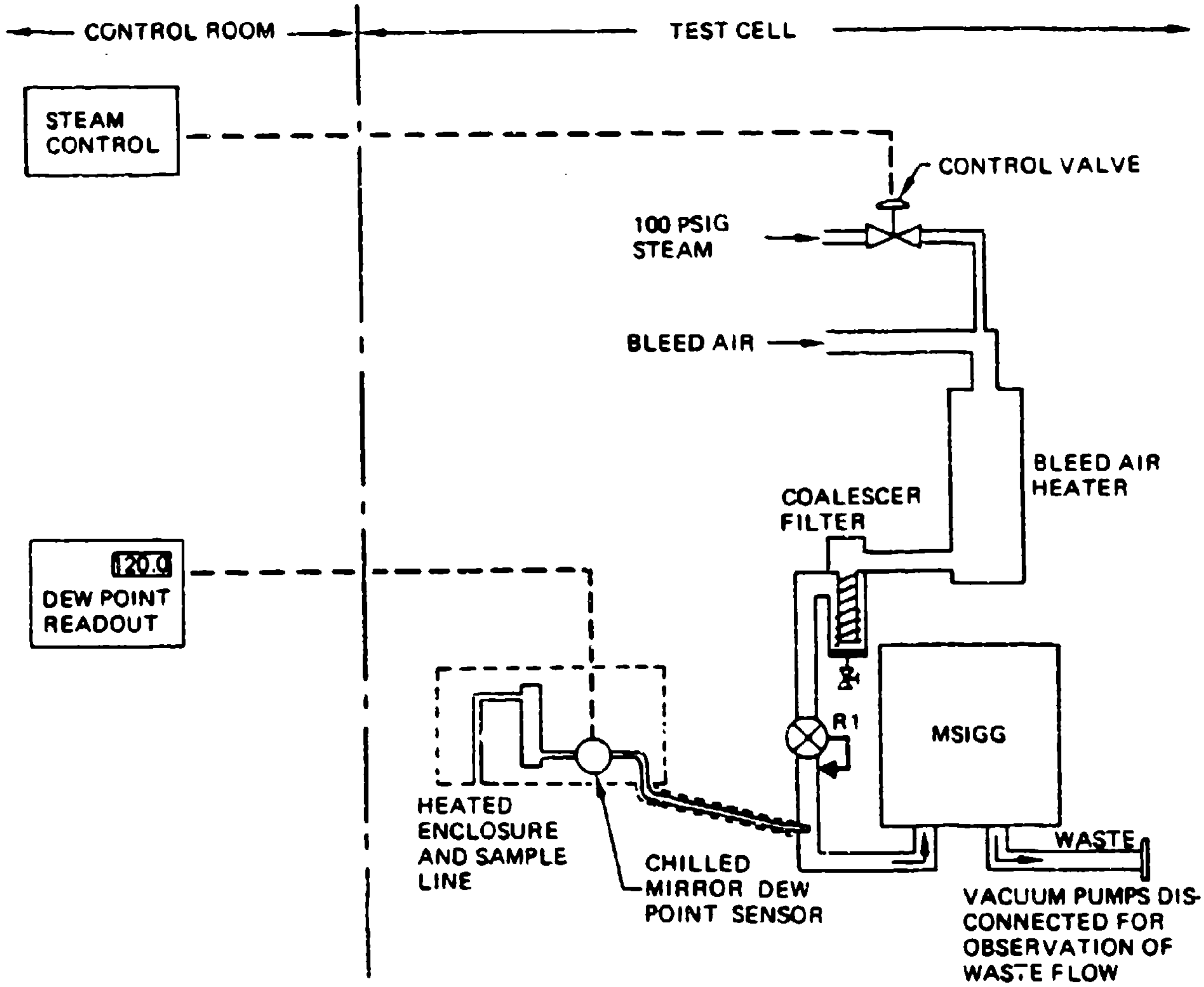


Figure C–1. MSIGG High Dewpoint Test Setup

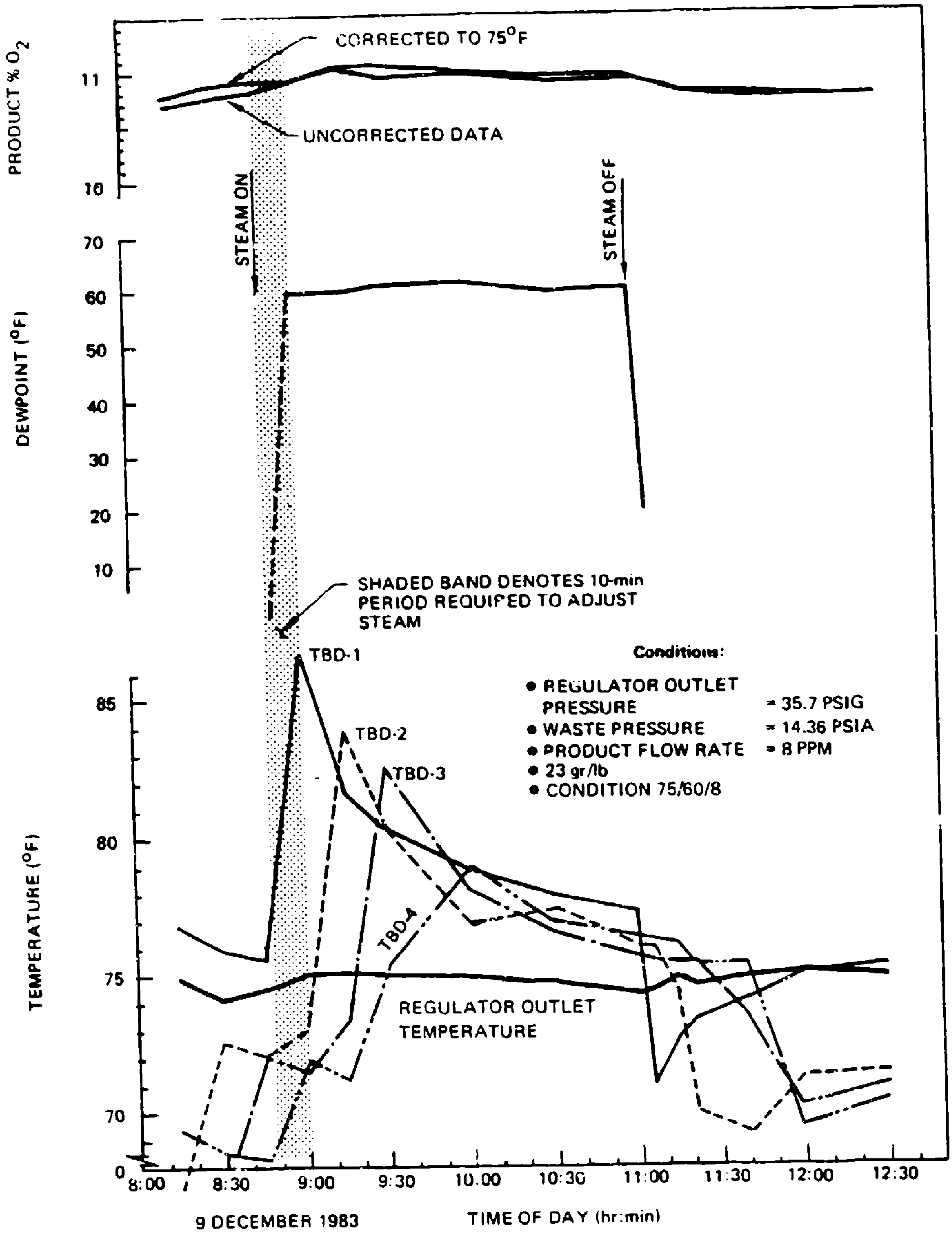


Figure C–2. MSIGG High Dewpoint Test – 75°F Temperature, 60°F Dewpoint, 22.8 gr/lb grains/lb implying an actual supersaturated condition with a total moisture level of 190 to 200 grains/lb entering the IGG coalescer filter. This condition was the most severe moisture level tested.

Procedure C (Descent into High Dew Point Environment)

Procedure C was designed to simulate a descent from high altitude, where the IGG is operating at 40°F with dry air, into a hot environment with ambient moisture levels of 156.7 grains/lb. The entire mass of the eight molecular sieve beds was first chilled to 40°F. then the bed inlet temperature and dew point were increased to 120°F. The IGG was operated with saturated inlet air and finally with dry bleed air to determine if any change in performance had occurred.

Procedure D (Descent with Subsequent Wet Shutdown)

Procedure D was identical to Procedure C in that D simulated a descent from high altitude, cold and dry conditions, into a hot moist environment. However, instead of returning to dry conditions prior to shutdown, the IGG was shutdown while operating with saturated 120°F air, thus trapping some water in the beds. The IGG was not operated again for up to 5 days. The purpose of this test was to determine if the water trapped in the "front" of the beds would diffuse into the remaining sieve material, poison it, and thereby degrade bed performance. Prior to this test, all moisture tests ended operation with dry air to purge the water from the beds after shutdown.

Procedure D was repeated three times with varying amounts of shutdown time at the end of the moisture injection phase.

Results of Moisture Tests

The detailed results for each moisture test with the MSIGG are presented in Figures C-2 through C-10 as plots of several important variables versus time. The product oxygen concentration is the variable of most interest, and was used to determine the extent of degradation in the MSIGG. During these tests, the inlet temperature, pressure, and product flow rate were held as constant as possible. Some variations did occur, especially in the bed temperature.

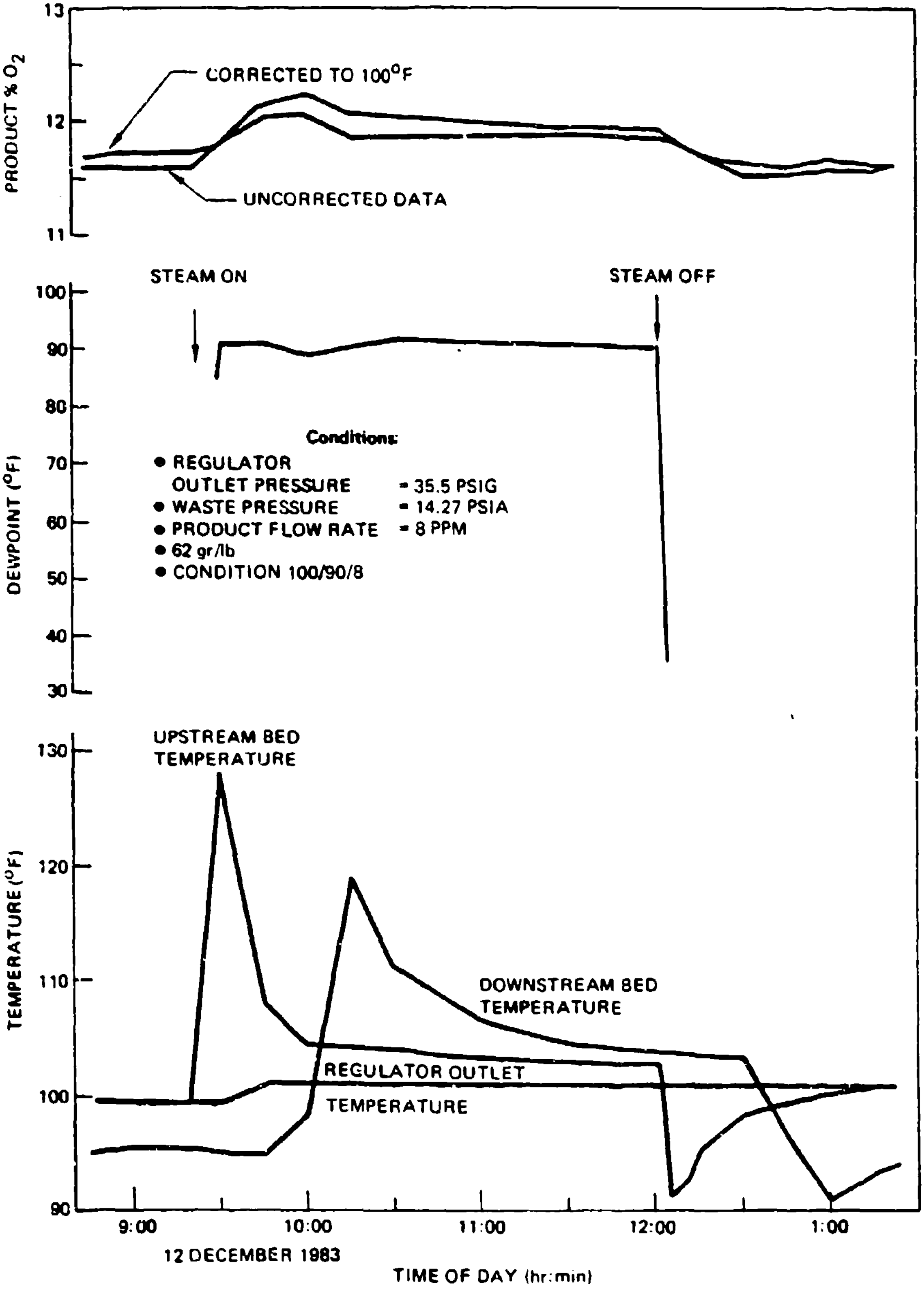


Figure C–3. MSIGG High Dewpoint Test – 100°F Temperature, 90°F Dewpoint, 62.1 gr/lb

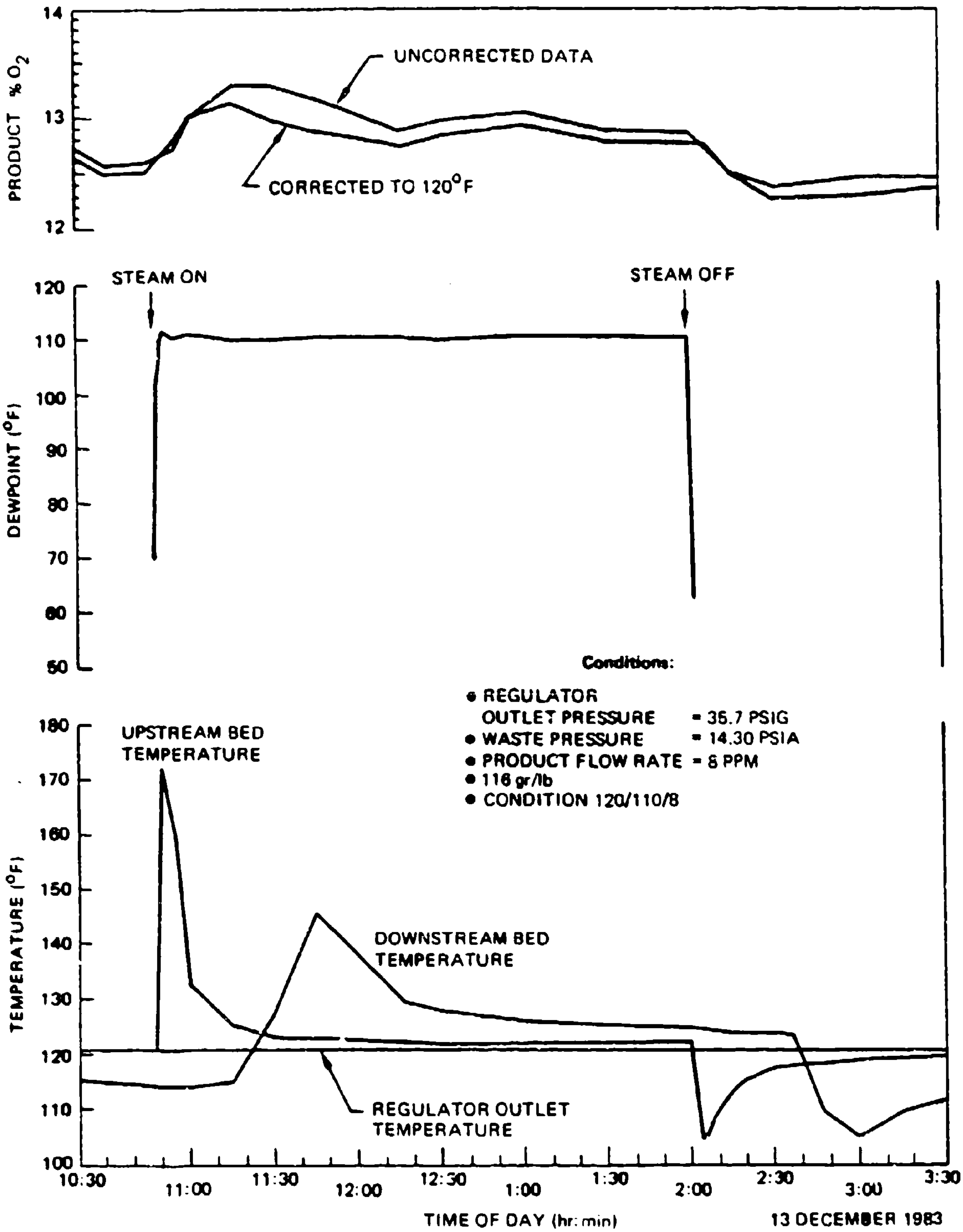


Figure C–4. MSIGG High Dewpoint Test – 120° F Temperature, 110° F Dewpoint, 115.8 gr/lb

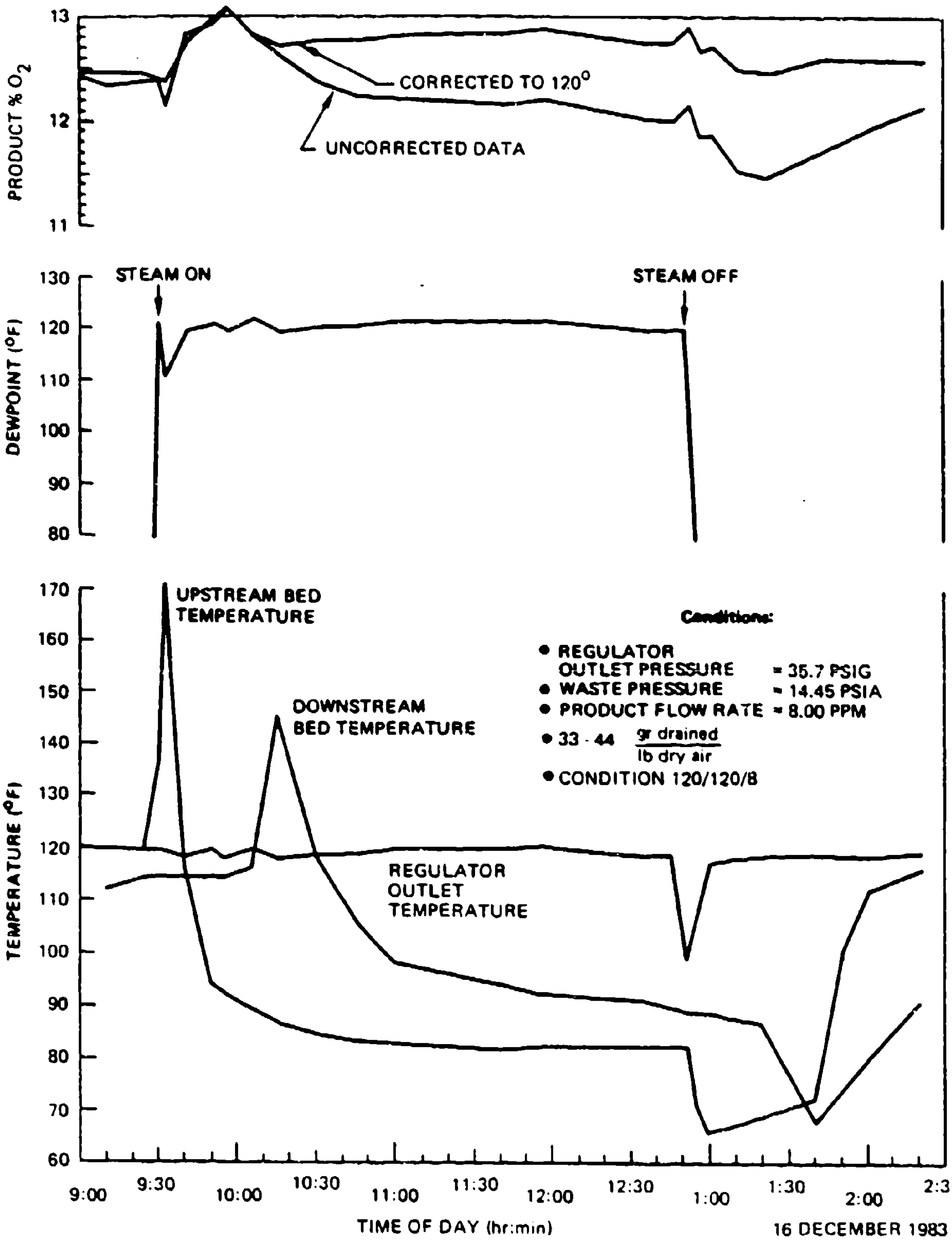


Figure C–5. MSIGG High Dewpoint Test – 120° F Temperature, 120° Dewpoint 156.7 gr/lb

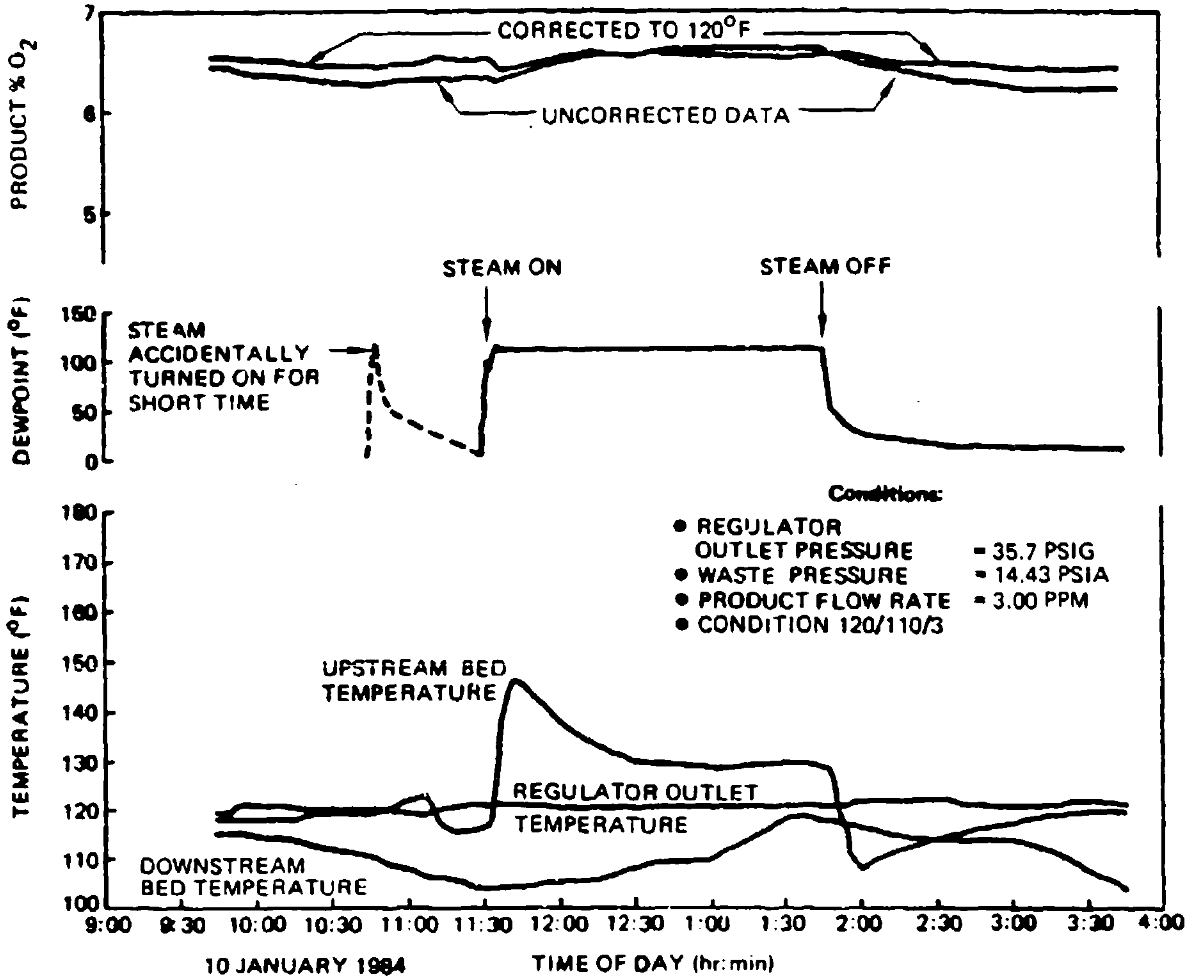


Figure C–6. MSIGG High Dewpoint Test – 120°F Temperature, 110°F Dewpoint, 116 gr/lb

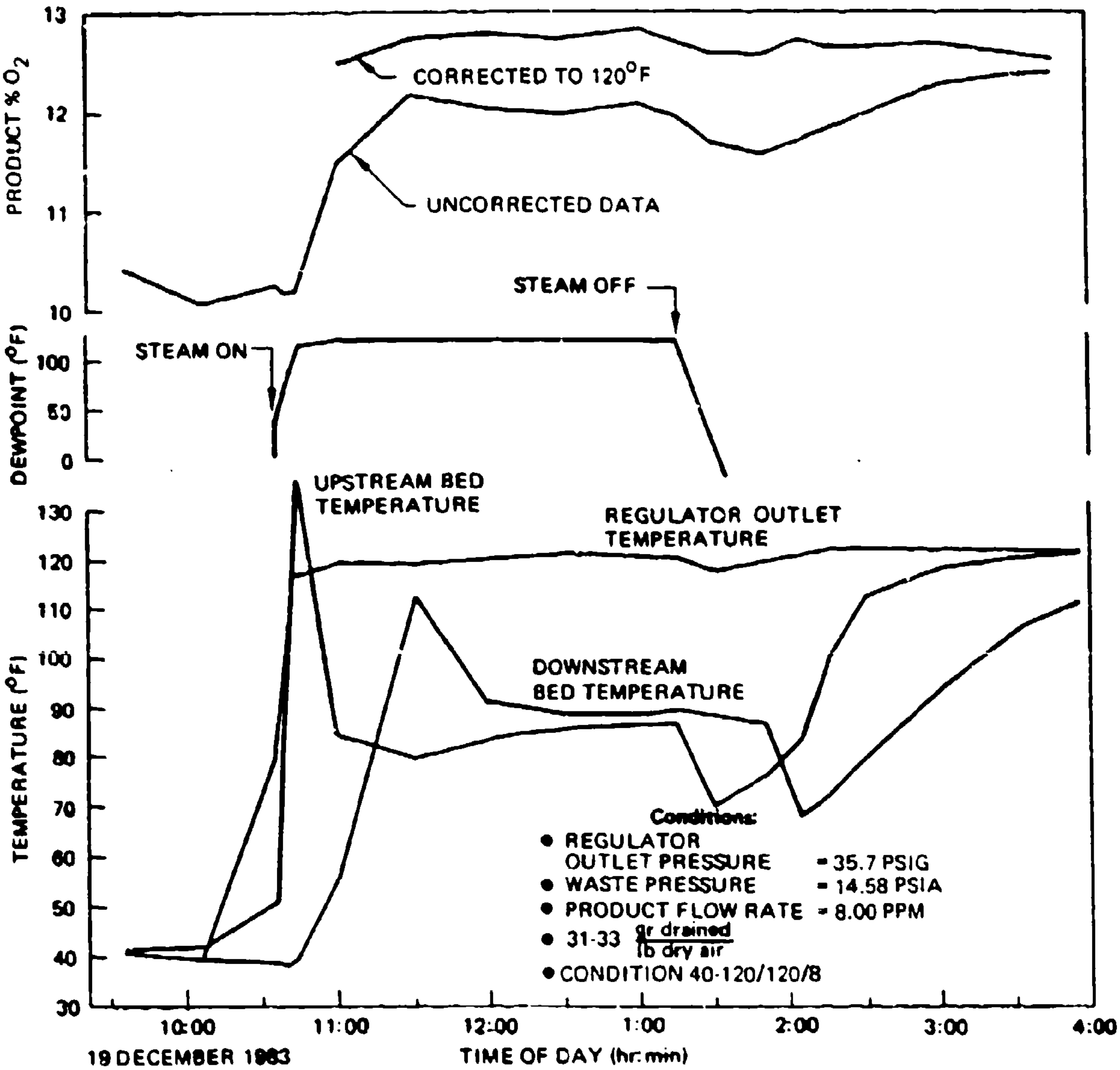


Figure C–7. MSIGG High Dewpoint Test – 40° - 120° F Temperature, 120° F Dewpoint, 156.7 gr/lb

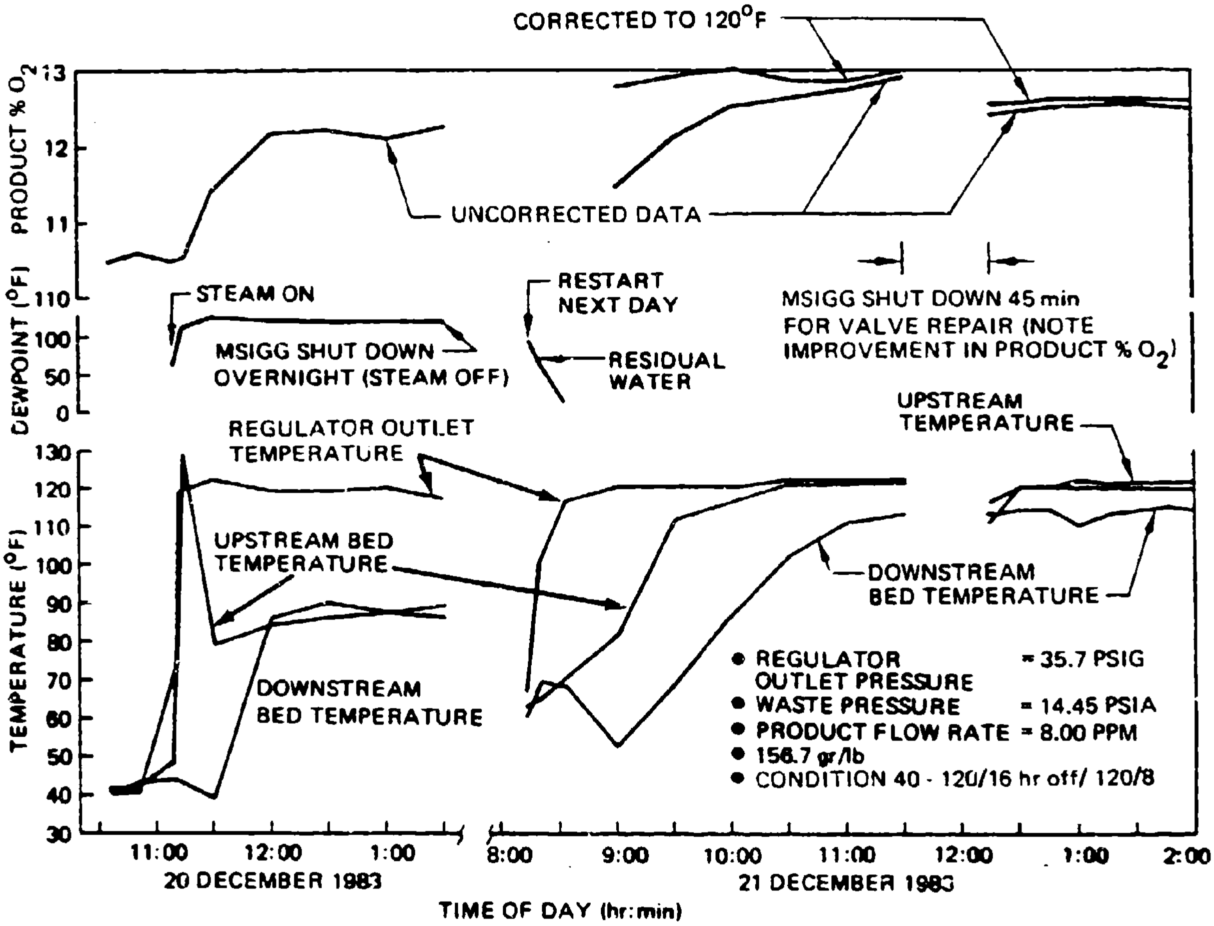


Figure C–8. MSIGG High Dewpoint Test – 40° - 120° F Temperature, at 120° F Dewpoint, Off 16 hr, Operate Dry at 120° F

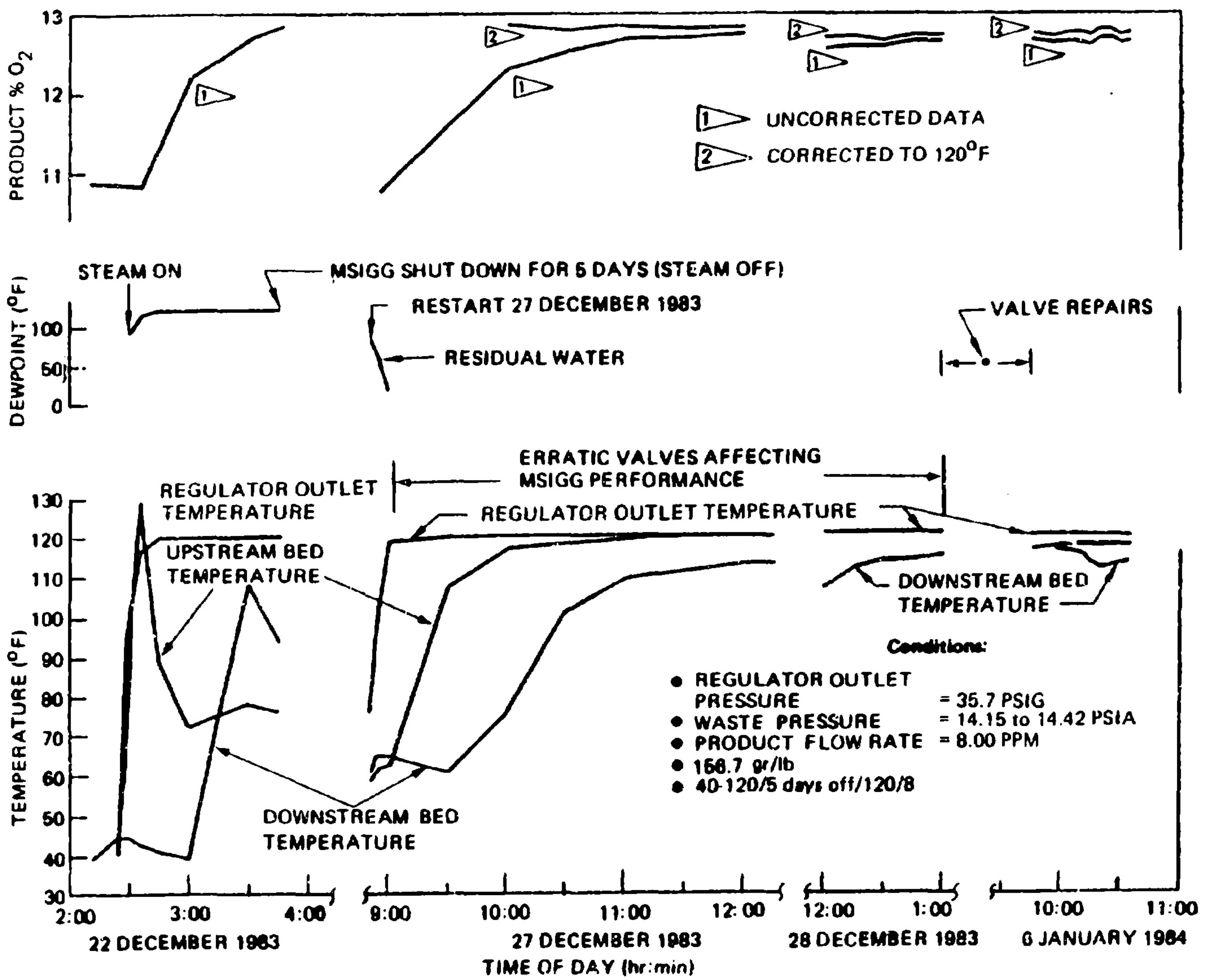


Figure C–9. MSIGG High Dewpoint Test – 40° - 120°F Temperature at 120°F Dewpoint, Off 5 Days, Operated Dry at 120°F

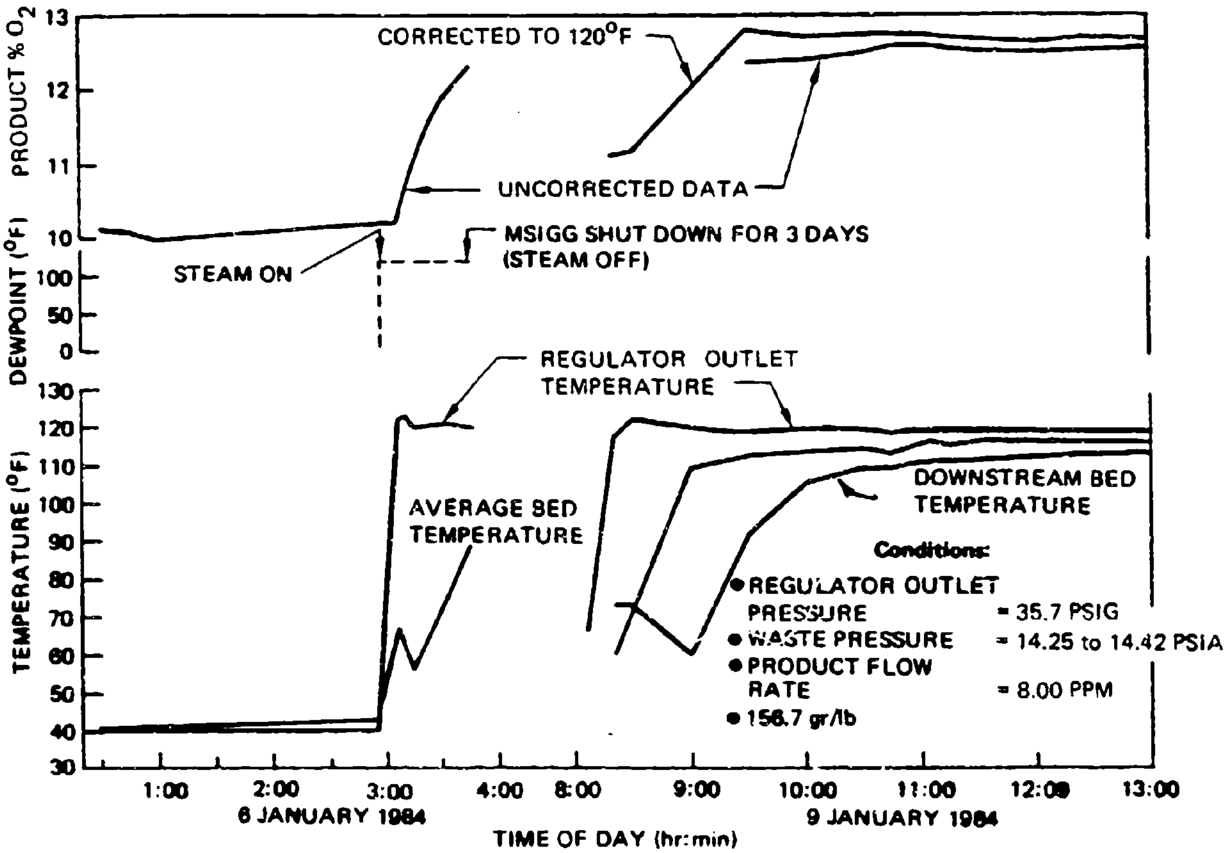


Figure C–10. MSIGG High Dewpoint Test – 40° - 120°F Temperature at 120°F Dewpoint, Off 3 Days, Operate Dry at 120°F

Therefore, what is presented is one product $\%O_2$ line that is corrected only for pressure and flow rate (shows combined effect of moisture and temperature) and another product $\%O_2$ line that is corrected for pressure, flow, and temperature (shows only the effect of moisture). When inlet conditions are saturated, the bed temperature drops significantly causing a gross performance improvement. The temperature corrected data surprisingly shows an improvement. However, the temperature correction factors are not accurate for the large corrections involved here (30 to 40^{o}F) and could explain the apparent anomaly. The dew point measured at the bed inlet pressure is also plotted to document the periods of time when steam is added to the inlet air as well as how fast the moisture level increases and decreases. Dew points below approximately 0^{o}F could not be measured with the instrumentation used but were assumed to indicate essentially dry air (less than 1.7 grains/lb). Inlet temperature and bed temperatures were also plotted to document the significant variations during moisture tests.

Results (Procedures A & B, Near Saturation & Saturation, Figures C-2 to C-6)

All of the tests conducted using procedure A or B are similar in that the steady state performance of the MSIGG is measured before, during, and after the time period of moisture injection. Any permanent degradation would show up as a shift in before and after oxygen concentration. A time period of one to two hours was required for the MSIGG to reach equilibrium. During the period of time when high dew point air was entering the MSIGG, the performance change was characterized by an initial increase in oxygen concentration which then decayed to an equilibrium value. In general, as the moisture levels increased, the changes in performance became greater. However, when the moisture levels increased to the point of saturation, a marked change in bed temperatures occurred. During all of the unsaturated moisture tests, the bed temperatures temporarily rose when moisture was first introduced and then temporarily decreased when dry conditions resumed. During the unsaturated moisture tests, these temperature transients always returned to equilibrium. However, during saturated tests, bed temperatures stabilized 30 to 40^{o}F below the inlet air temperature. This observation is evident when Figures C-4 and C-5 are compared.

A potential explanation for this surprising drop in bed temperature is offered here. Free water could have been continuously re-entrained at the coalescer filter, entering and undergoing a phase change in the bed (evaporating), thereby causing a drop in bed temperature. This explanation agrees with the observation that liquid water dripped from the waste manifold, which only occurred during tests with saturated inlet conditions.

In addition, if enough moisture is added to saturate the bleed air, overall MSIGG performance is actually improved because the drop in bed temperature is significant enough to more than offset the effect of moisture alone.

Results (Procedure C, Descent into High Dew Point Environment, Figure C-7)

Since Procedure C does not begin and end at the same temperature, a before and after comparison of performance cannot be made. However, the final MSIGG performance is at 120^{o}F (dry) and can be compared to the 120^{o}F performance of other tests. Note, the bed temperatures respond very similarly to those in procedure B (saturated @ 120^{o}F). No significant permanent shift in performance was observed during the single Procedure C test.

Results (Procedure D, Wet Shutdown, Figures C-8 to C-10)

Procedure D was repeated three times with varying amounts of shutdown time at the end of the moisture injection phase. The bed temperatures responded as in Procedure C, and no significant shift in performance was noted due to a "wet" shutdown. However, there did appear to be a slight ($\approx$ 0.3%O_2) change in 120^{o}F dry performance after the second shutdown which lasted 5 days. The next time Procedure D was repeated (3 day shutdown), the shift in performance did not recur, in fact, some performance was regained ($\approx$ 0.1%O_2).

APPENDIX D

Accuracy of O_2 Concentration Measurement for MSIGG Moisture Tests

The following is a discussion of the errors involved in determining performance characteristics of the MSIGG as a result of moisture testing, specifically in determining whether degradation has taken place.

Four input variables have been identified that affect the O_2 quality of the IGG product; these are expressed as inputs to the following general function (f):

$$\%O_2 = f\ (W,\ PREGOT,\ PWASTE,\ T)$$

where,

$\%O_2$	=	Product $\%O_2$
W	=	Product mass flow - PPM
PREGOT	=	Inlet supply pressure - PSIG
PWASTE	=	Waste flow pressure - PSIA
T	=	Average MSIGG bed temperature - ^{o}F

To make a judgement about trends in the $\%O_2$ levels, one must first calculate the maximum spread expected in the concentration measurement, given a series of tests with constant input variables. This spread could be due to drift in the Beckman OM-11 Oxygen Analyzer given as $\pm 0.1\ \%O_2$ (in measurement units) or due to changes in the input variables that go undetected because of errors in their measurement.

The maximum error in $\%O_2$ measurement can be expressed as follows:

$$\Delta_{max} = \Delta_{OM\text{-}11} + \Delta_{W} + \Delta_{PREGOT} + \Delta_{PWASTE} + \Delta_{T}$$

where,

Δ_{max} = Maximum $\%O_2$ error

$\Delta_{OM\text{-}11}$ = $\pm 0.1\%O_2$ (As per Beckman)

$$\Delta_W = \left[\frac{\partial f}{\partial W}\right] \delta W$$

$$\Delta_{PREGOT} = \left[\frac{\partial f}{\partial PREGOT}\right] \delta PREGOT$$

$$\Delta_{PWASTE} = \left[\frac{\partial f}{\partial PWASTE}\right] \delta PWASTE$$

$$\Delta_T = \left[\frac{\partial f}{\partial T}\right] \delta T$$

δW	= Product Flow Measurement Error
$\delta PREGOT$	= Inlet Pressure Measurement Error
$\delta PWASTE$	= Waste Pressure Measurement Error
δT	= Temperature Measurement Error

Actual values for the above expressions were determined experimentally or from manufacturer's data and are given below:

Variable (x)	δx	$\frac{\partial f}{\partial x}$ (Evaluated @ 8 PPM, 35.7 psig, 14.7 psia, 120oF)
$\%O_2$	$0.1\%O_2$	N/A
W	0.16 PPM	$0.8\%O_2$/PPM
PREGOT	0.25 PSI	$0.26\%O_2$/PSI
PWASTE	0.75 PSI	$0.45\%O_2$/PSI
T	2^oF	$0.23\%O_2/^oF$

Thus, the maximum O_2 measurement error in either direction is:

$$\Delta_{max} = \pm 0.38\%O_2$$

A more probable error would be given by the root sum of the squares (RSS) formula or standard deviation as follows:

$$\Delta_{RSS} = \pm \Delta^2_{OM-11} + \Delta^2_W + \Delta^2_{PREGOT} + \Delta^2_{PWASTE} + \Delta^2_T$$

$$\Delta_{RSS} = \pm 0.19\%O_2$$

In reviewing the moisture test results, it is seen that 8 data points are recorded for the $\%O_2$ concentrations, as follows:

Date	Product $\%O_2$
13 December	12.62
13 December	12.57
16 December	12.44
16 December	12.62
19 December	12.47
21 December	12.58
6 January	12.86
9 January	12.74

If the sample is normally distributed, the mean is calculated as:

$\%O_2 = 12.61\%$

and the standard deviation $\sigma O_2 = 0.14\%O_2$

Thus, the measured standard deviation is consistent with the expected deviation based on instrument error and supporting the conclusion that there is no measurable degradation of the MSIGG due to the moisture tests conducted.

APPENDIX E

KC-135 Mission Profile Data

This appendix contains the original KC-135 design mission and the actual detailed set point schedules that were used during the mission simulations reported on in Sections 5.3 and 5.4 (Mission A and B). Also contained in this appendix is the On-Line ACM model used to predict the ACM outlet pressures during mission simulations with the PMIGG.

Table E–1. Standard Day Mission Data (FROM REFERENCE 1)

Point	Altitude (ft)	Mach number	Fuel flow (lb/h)	Ullage (gal)	Mission time (hr)	Bleed air pressure PSIA	Bleed air temperature (F°)
1	0	0.423	28,930	1,806	0.05	135.6	664
2	15,000	0.565	22,090	2,576	0.22	98.9	633
3	33,000	0.780	13,140	3,652	0.62	58.1	558
4	37,000	0.580	11,660	5,036	1.37	55.5	508
5	30,000	0.682	9,570	9,012	1.95	49.3	495
6	45,500	0.780	7,320	13,552	3.11	32.8	534
7	46,000	0.780	4,880	14,168	3.64	33.8	561
8	30,000	0.670	7,840	14,238	3.71	44.1	465
9	30,000	0.696	6,000	14,782	4.21	48.4	494
10	15,000	0.515	5,420	14,936	4.29	57.2	476
11	2,500	0.221	7,700	15,398	4.54	60.1	388
12	27,000	0.650	5,720	16,168	4.83	51.0	476
13	15,000	0.515	5,420	16,322	4.95	57.2	476
14	0	0.378	16,970	16,476	5.10	96.7	586

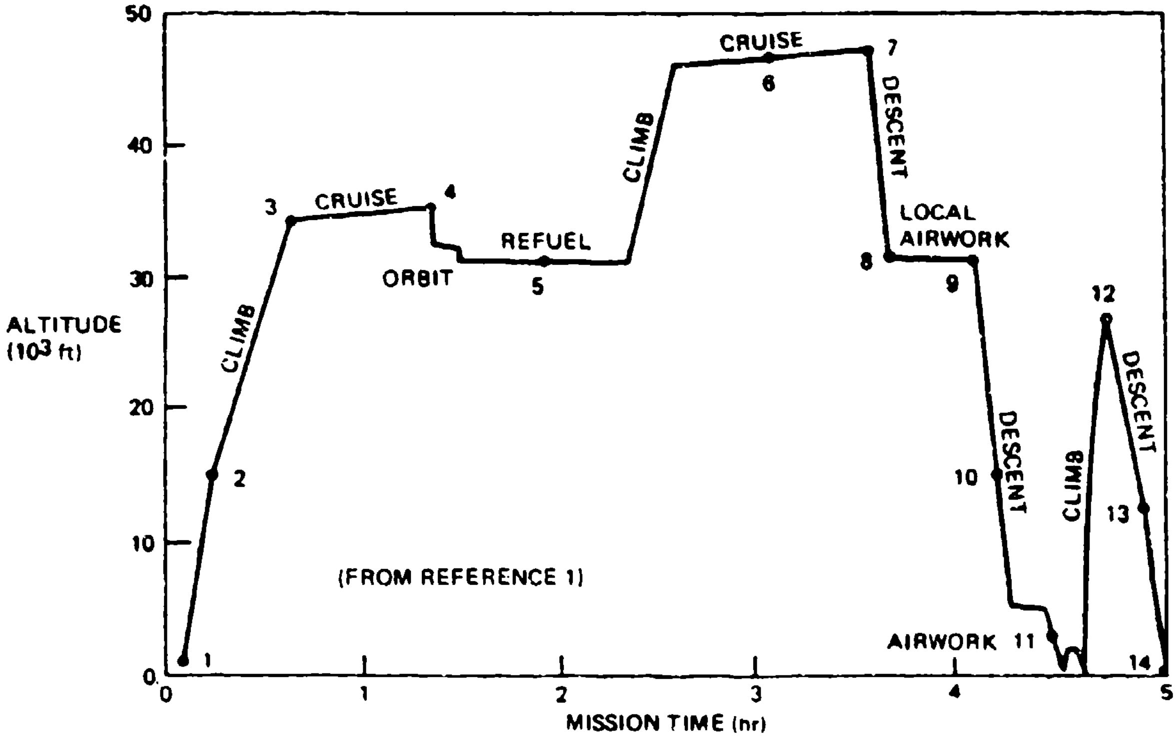


Figure E–1. KC–135 Tanker Design Mission

Table E-2

MSIGG KC-135 MISSION A SET POINT SCHEDULE

Mission Time (Min)	PAMB (PSIA)	WALL TEMPS (°F) TOP	BOTTOM	GPM OUT	GAL* OUT	PBLEED (PSIA)	PWASTE (PSIA)	RAM** Recovery TEMP (°F)
0.0	14.7D	59.D	59.D	0.0D	0.D	162.0D	14.7D	59.D
3.0	14.7C	76.C	75.C	0.0C	0.C	162.0C	14.7C	78.D
10.0	10.1C	47.C	48.C	2.4C	17.C	133.0C	10.1C	48.C
14.0	8.3C	31.C	32.C	1.6C	23.C	120.4C	8.3C	35.C
18.5	6.7C	23.C	25.C	1.6C	30.C	108.5C	6.7C	24.C
24.5	5.4C	13.C	14.C	1.7C	40.C	97.5C	5.4C	12.C
32.5	4.3C	-1.C	0.C	1.4C	52.C	85.5C	4.3C	-1.C
40.0	3.6C	-15.C	-14.C	1.5C	63.C	77.3C	3.6C	-9.C
79.5	3.6C	-19.C	-17.C	1.1C	105.C	68.5D	3.6C	-14.C
82.0	4.2C	-17.C	-17.C	0.5C	107.C	67.2C	4.2C	-13.C
90.0	4.2C	-9.C	-8.C	1.0C	115.C	67.2C	4.2C	-4.D
90.8	4.4C	-13.C	-13.C	0.5C	115.C	60.9C	4.4C	-10.C
109.4	4.4C	-13.C	-13.C	0.8C	130.C	60.9C	4.4C	-10.C
117.0	4.4C	-13.C	-12.C	14.2D	238.C	60.9C	4.4C	-10.C
124.0	4.4C	-13.C	-12.C	14.2C	338.C	60.9C	4.4C	-10.C
140.0	4.4C	-7.C	-6.C	0.8D	351.C	60.9C	4.4C	-2.D
143.0	3.5C	-10.C	-8.C	1.0C	354.C	72.0D	3.5C	-6.C
147.0	2.7C	-4.C	-2.C	0.8C	357.C	68.0C	2.7C	-12.C
158.0	2.1C	-27.C	-24.C	1.1C	370.C	44.5C	2.1C	-23.C
187.0	2.1C	-27.C	-25.C	0.6C	388.C	39.4D	2.1C	-23.C
218.0	2.1C	-27.C	-25.C	0.6C	407.C	38.5C	2.1C	-23.C
222.7	4.4C	-14.C	-14.C	0.5C	409.C	63.5C	4.4C	-11.C
240.0	4.4C	-11.C	-11.C	0.7C	434.C	54.3D	4.4C	-8.C
244.2	8.3C	28.C	26.C	0.5C	436.C	70.1C	8.3C	31.C
247.2	12.2C	68.C	64.C	0.4C	437.C	79.2C	12.2C	71.C
261.2	12.2C	60.C	57.C	1.2C	454.C	109.8D	12.2C	62.D
262.0	13.4C	68.C	64.C	0.4C	454.C	82.9D	13.4C	70.C
262.6	14.4C	74.C	69.C	0.4C	455.C	83.8C	14.4C	76.C
263.0	13.7C	79.C	74.C	1.2C	456.C	157.3D	13.7C	82.C
269.3	13.7C	70.C	65.C	1.4C	464.C	157.3D	13.7C	72.D
270.0	14.7C	75.C	70.C	0.3C	465.C	81.4D	14.7C	77.C
274.0	8.3C	31.C	33.C	2.2C	473.C	120.0D	8.3C	35.C
278.3	5.0C	-5.C	-4.C	1.7C	480.C	61.1C	5.0C	-1.C
281.5	8.3C	28.C	27.C	0.5C	482.C	70.1C	8.3C	31.C
286.0	14.7C	72.C	72.C	0.6C	484.C	122.9C	14.7C	74.C

* Gal in tank = 524 - GALOUT

** $T_{BLEED} = T_{RECOVERY} + 10^{o}F \geq 40^{o}F$

C Denotes continuous linear interpolation between set points.

D Denotes a single discrete value for the set point.

Table E-3

MSIGG KC-135 MISSION B SET POINT SCHEDULE

Mission Time (Min)	PAMB (PSIA)	WALL TEMPS (°F) TOP	BOTTOM	GPM OUT	GAL* OUT	PBLEED (PSIA)	PWASTE (PSIA)	RAM Recovery TEMP (°F)
0.0	14.7D	59.D	59.D	0.0D	0.D	162.0D	14.7D	59.D
3.0	14.7C	76.C	75.C	0.0C	0.C	162.0C	14.7C	78.D
10.0	10.1C	47.C	48.C	2.4C	17.C	133.0C	10.1C	48.C
14.0	8.3C	31.C	32.C	1.6C	23.C	120.4C	8.3C	35.C
18.5	6.7C	23.C	25.C	1.6C	30.C	108.5C	6.7C	24.C
24.5	5.4C	13.C	14.C	1.7C	40.C	97.5C	5.4C	12.C
32.5	4.3C	-1.C	0.C	1.4C	52.C	85.5C	4.3C	-1.C
40.0	3.6C	-15.C	-14.C	1.5C	63.C	77.3C	3.6C	-9.C
79.5	3.6C	-19.C	-17.C	1.1C	105.C	68.5D	3.6C	-14.C
82.0	4.2C	-17.C	-17.C	0.5C	107.C	67.2C	4.2C	-13.C
90.0	4.2C	-9.C	-8.C	1.0C	115.C	67.2C	4.2C	-4.D
90.8	4.4C	-13.C	-13.C	0.5C	115.C	60.9C	4.4C	-10.C
109.4	4.4C	-13.C	-13.C	0.8C	130.C	60.9C	4.4C	-10.C
117.0	4.4C	-13.C	-12.C	14.2D	238.C	60.9C	4.4C	-10.C
124.0	4.4C	-13.C	-12.C	14.2C	338.C	60.9C	4.4C	-10.C
140.0	4.4C	-7.C	-6.C	0.8D	351.C	60.9C	4.4C	-2.D
143.0	3.5C	-10.C	-8.C	1.0C	354.C	72.0D	3.5C	-6.C
147.0	2.7C	-4.C	-2.C	0.8C	357.C	68.0C	2.7C	-12.C
158.0	2.1C	-27.C	-24.C	1.1C	370.C	44.5C	2.1C	-23.C
187.0	2.1C	-27.C	-25.C	0.6C	388.C	39.4D	2.1C	-23.C
218.0	2.1C	-27.C	-25.C	0.6C	407.C	38.5C	2.1C	-23.C
222.7	4.4C	-14.C	-14.C	0.5C	409.C	63.5C	4.4C	-11.C
240.0	4.4C	-11.C	-11.C	0.7C	434.C	54.3D	4.4C	-8.C
245.1	8.3C	28.C	26.C	0.5C	436.C	70.1C	8.3C	31.C
249.0	12.2C	68.C	64.C	0.4C	437.C	79.2C	12.2C	71.C
263.0	12.2C	60.C	57.C	1.2C	454.C	109.8D	12.2C	62.D
263.8	13.4C	68.C	64.C	0.4C	454.C	82.9D	13.4C	70.C
264.4	14.4C	74.C	69.C	0.4C	455.C	83.8C	14.4C	76.C
264.8	13.7C	79.C	74.C	1.2C	456.C	157.3D	13.7C	82.C
271.1	13.7C	70.C	65.C	1.4C	464.C	157.3D	13.7C	72.D
271.8	14.7C	75.C	70.C	0.3C	465.C	81.4D	14.7C	77.C
275.8	8.3C	31.C	33.C	2.2C	473.C	120.0D	8.3C	35.C
280.1	5.0C	-5.C	-4.C	1.7C	480.C	61.1C	5.0C	-1.C
285.1	8.3C	28.C	27.C	0.5C	482.C	70.1C	8.3C	31.C
293.3	14.7C	72.C	72.C	0.6C	484.C	122.9C	14.7C	74.C

* Gal in tank = 524 - GALOUT

** $T_{BLEED} = T_{RECOVERY} + 10^{o}F \geq 40^{o}F$

C Denotes continuous linear interpolation between set points.

D Denotes a single discrete value for the set point.

Table E-4

PMIGG KC-135 MISSION A SET POINT SCHEDULE

Mission Time (Min)	PAMB (PSIA)	WALL TEMPS (°F) TOP	BOTTOM	GPM OUT	GAL* OUT	PBLEED (PSIA)	PWASTE (PSIA)	TBLEED (°F)
0.0	14.7D	59.D	59.D	0.0D	0.D		14.7D	75.D
3.0	14.7C	76.C	75.C	0.0C	0.C		14.7C	75.D
10.0	10.1C	47.C	48.C	2.4C	17.C		10.1C	75.C
14.0	8.3C	31.C	32.C	1.6C	23.C		8.3C	75.C
18.5	6.7C	23.C	25.C	1.6C	30.C		6.7C	75.C
24.5	5.4C	13.C	14.C	1.7C	40.C	PBLEED	5.4C	75.C
32.5	4.3C	-1.C	0.C	1.4C	52.C		4.3C	75.C
40.0	3.6C	-15.C	-14.C	1.5C	63.C		3.6C	75.C
79.5	3.6C	-19.C	-17.C	1.1C	105.C		3.6C	75.C
82.0	4.2C	-17.C	-17.C	0.5C	107.C	Computed	4.2C	75.C
90.0	4.2C	-9.C	-8.C	1.0C	115.C		4.2C	75.D
90.8	4.4C	-13.C	-13.C	0.5C	115.C		4.4C	75.C
109.4	4.4C	-13.C	-13.C	0.8C	130.C		4.4C	75.C
117.0	4.4C	-13.C	-12.C	14.2D	238.C	By	4.4C	75.C
124.0	4.4C	-13.C	-12.C	14.2C	338.C		4.4C	75.C
140.0	4.4C	-7.C	-6.C	0.8D	351.C		4.4C	75.D
143.0	3.5C	-10.C	-8.C	1.0C	354.C		3.5C	75.C
147.0	2.7C	-4.C	-2.C	0.8C	357.C	ON-LINE	2.7C	75.C
158.0	2.1C	-27.C	-24.C	1.1C	370.C		2.1C	75.C
187.0	2.1C	-27.C	-25.C	0.6C	388.C		2.1C	75.C
218.0	2.1C	-27.C	-25.C	0.6C	407.C		2.1C	75.C
222.7	4.4C	-14.C	-14.C	0.5C	409.C	ACM	4.4C	75.C
240.0	4.4C	-11.C	-11.C	0.7C	434.C		4.4C	75.C
244.2	8.3C	28.C	26.C	0.5C	436.C		8.3C	75.C
247.2	12.2C	68.C	64.C	0.4C	437.C		12.2C	75.C
261.2	12.2C	60.C	57.C	1.2C	454.C	Model	12.2C	75.D
262.0	13.4C	68.C	64.C	0.4C	454.C		13.4C	75.C
262.6	14.4C	74.C	69.C	0.4C	455.C		14.4C	75.C
263.0	13.7C	79.C	74.C	1.2C	456.C		13.7C	75.C
269.3	13.7C	70.C	65.C	1.4C	464.C		13.7C	75.D
270.0	14.7C	75.C	70.C	0.3C	465.C		14.7C	75.C
274.0	8.3C	31.C	33.C	2.2C	473.C		8.3C	75.C
278.3	5.0C	-5.C	-4.C	1.7C	480.C		5.0C	75.C
281.5	8.3C	28.C	27.C	0.5C	482.C		8.3C	75.C
286.0	14.7C	72.C	72.C	0.6C	484.C		14.7C	75.C

* Gal in tank = 524 - GALOUT

C Denotes continuous linear interpolation between set points.

D Denotes a single discrete value for the set point.

Table E-5

PMIGG KC-135 MISSION B SET POINT SCHEDULE

Mission Time (Min)	PAMB (PSIA)	WALL TEMPS (°F) TOP	BOTTOM	GPM OUT	GAL* OUT	PBLEED (PSIA)	PWASTE (PSIA)	TBLEED (°F)
0.0	14.7D	59.D	59.D	0.0D	0.D		14.7D	75.D
3.0	14.7C	76.C	75.C	0.0C	0.C		14.7C	75.D
10.0	10.1C	47.C	48.C	2.4C	17.C		10.1C	75.C
14.0	8.3C	31.C	32.C	1.6C	23.C		8.3C	75.C
18.5	6.7C	23.C	25.C	1.6C	30.C		6.7C	75.C
24.5	5.4C	13.C	14.C	1.7C	40.C	PBLEED	5.4C	75.C
32.5	4.3C	-1.C	0.C	1.4C	52.C		4.3C	75.C
40.0	3.6C	-15.C	-14.C	1.5C	63.C		3.6C	75.C
79.5	3.6C	-19.C	-17.C	1.1C	105.C		3.6C	75.C
82.0	4.2C	-17.C	-17.C	0.5C	107.C	Computed	4.2C	75.C
90.0	4.2C	-9.C	-8.C	1.0C	115.C		4.2C	75.D
90.8	4.4C	-13.C	-13.C	0.5C	115.C		4.4C	75.C
109.4	4.4C	-13.C	-13.C	0.8C	130.C		4.4C	75.C
117.0	4.4C	-13.C	-12.C	14.2D	238.C	By	4.4C	75.C
124.0	4.4C	-13.C	-12.C	14.2C	338.C		4.4C	75.C
140.0	4.4C	-7.C	-6.C	0.8D	351.C		4.4C	75.D
143.0	3.5C	-10.C	-8.C	1.0C	354.C		3.5C	75.C
147.0	2.7C	-4.C	-2.C	0.8C	357.C	ON-LINE	2.7C	75.C
158.0	2.1C	-27.C	-24.C	1.1C	370.C		2.1C	75.C
187.0	2.1C	-27.C	-25.C	0.6C	388.C		2.1C	75.C
218.0	2.1C	-27.C	-25.C	0.6C	407.C		2.1C	75.C
222.7	4.4C	-14.C	-14.C	0.5C	409.C	ACM	4.4C	75.C
240.0	4.4C	-11.C	-11.C	0.7C	434.C		4.4C	75.C
245.1	8.3C	28.C	26.C	0.5C	436.C		8.3C	75.C
249.0	12.2C	68.C	64.C	0.4C	437.C		12.2C	75.C
263.0	12.2C	60.C	57.C	1.2C	454.C	Model	12.2C	75.D
263.8	13.4C	68.C	64.C	0.4C	454.C		13.4C	75.C
264.4	14.4C	74.C	69.C	0.4C	455.C		14.4C	75.C
264.8	13.7C	79.C	74.C	1.2C	456.C		13.7C	75.C
271.1	13.7C	70.C	65.C	1.4C	464.C		13.7C	75.D
271.8	14.7C	75.C	70.C	0.3C	465.C		14.7C	75.C
275.8	8.3C	31.C	33.C	2.2C	473.C		8.3C	75.C
280.1	5.0C	-5.C	-4.C	1.7C	480.C		5.0C	75.C
285.1	8.3C	28.C	27.C	0.5C	482.C		8.3C	75.C
293.3	14.7C	72.C	72.C	0.6C	484.C		14.7C	75.C

* Gal in tank = 524 - GALOUT

C Denotes continuous linear interpolation between set points.

D Denotes a single discrete value for the set point.

CURVE FIT COORDINATES (FROM AIRESEARCH PREDICTED PERFORMANCE DATA)

P AMB	REG NO. 2	
14.7	107.5	HIGH MODE
9.0	98.6	
3.9	81.0	
1.65	50.0	
14.7	89.5	LOW MODE
8.3	82.2	
2.23	69.4	
2.0	50.0	

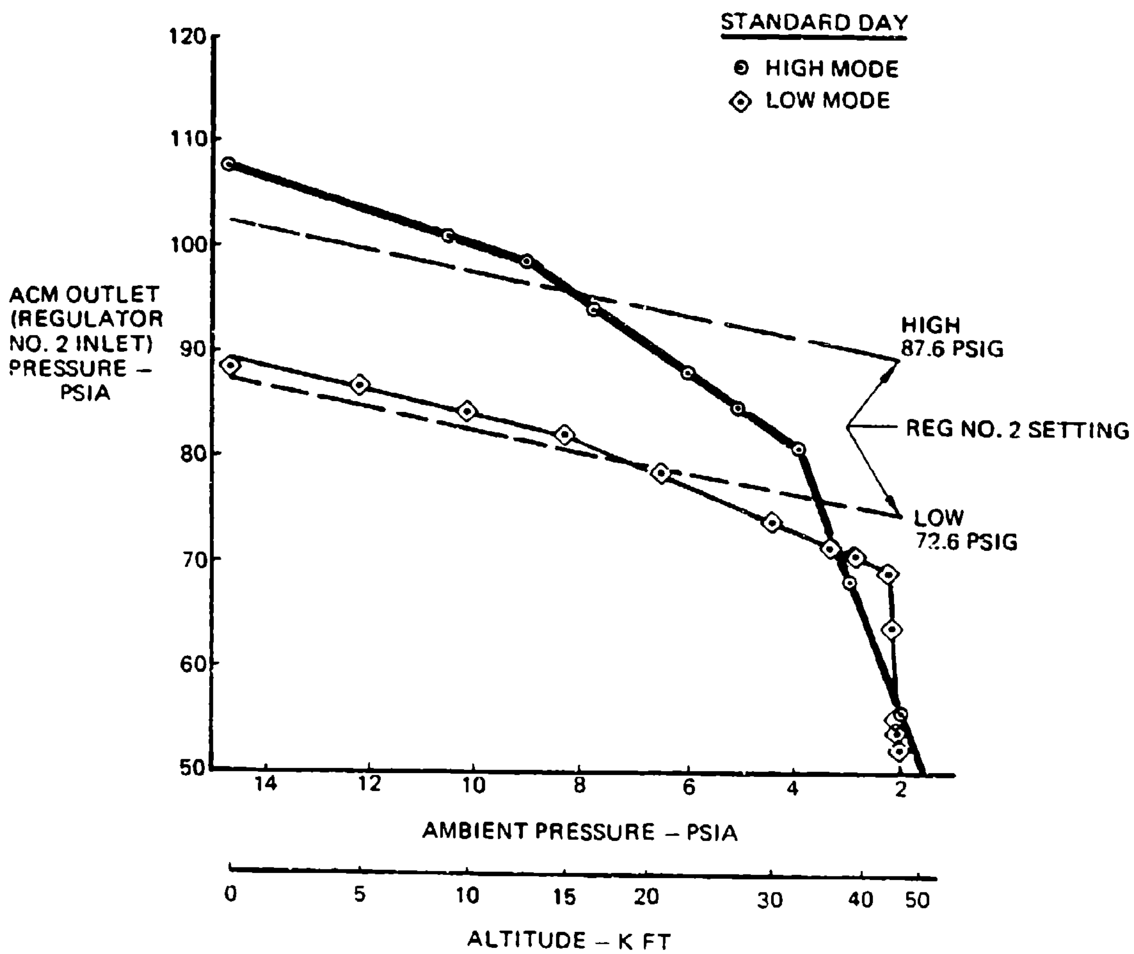


Figure E–2. PMIGG ACM On–line Model – Standard Day (Used for Mission Simulations)

APPENDIX F

MSIGG Steady State Performance Data

MSIGG

STANDARD PERFORMANCE TEST AT SEA LEVEL AND 75 F NOMINAL

WASTE PRES (PSIA)	AVG BED TEMP (F)	BED INLET PRES (PSID)	BED INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
14.56	80	15.96	79	0.11	8.95	1.2	1.57
14.56	80	15.71	79	0.50	9.23	5.4	3.08
14.56	79	15.54	80	1.02	9.61	10.6	5.54
14.56	79	15.95	79	1.98	10.58	18.7	8.97
14.56	78	15.87	79	3.01	11.38	26.4	11.85
14.75	77	20.07	79	0.11	10.88	1.0	1.34
14.71	77	19.88	78	0.51	11.17	4.6	2.25
14.72	76	19.95	78	1.01	11.72	8.6	3.89
14.71	77	20.12	78	2.00	12.70	15.7	7.01
14.69	76	19.66	88	3.02	13.29	22.7	10.12
14.70	78	20.06	85	4.10	14.37	28.5	11.86
14.76	81	25.90	81	0.10	13.64	0.7	1.48
14.76	81	25.51	80	1.01	14.33	7.0	2.89
14.76	81	25.11	79	3.01	15.87	19.0	7.54
14.76	80	25.14	78	5.05	17.74	28.5	11.01
14.76	79	25.83	78	7.95	19.90	39.9	13.66
14.66	80	30.46	79	0.11	15.59	0.7	1.23
14.66	79	30.08	77	1.04	16.30	6.4	2.65
14.68	78	30.03	79	3.03	18.19	16.7	6.47
14.68	79	30.25	80	5.02	19.74	25.4	9.47
14.68	77	29.81	77	8.00	21.92	36.5	12.55
14.71	76	40.11	78	.10	19.84	0.5	1.17
14.71	75	40.60	78	.96	20.89	4.6	1.93
14.70	75	40.71	77	3.01	23.17	13.0	4.33
14.70	75	40.49	77	5.07	24.73	20.5	6.89
14.71	75	40.15	78	8.02	26.37	30.4	9.62
14.72	75	40.18	78	9.96	28.65	34.8	11.13
14.71	75	40.51	79	12.06	30.17	40.0	12.47
14.69	76	55.41	78	0.11	26.30	0.4	1.34
14.67	75	55.68	78	1.06	27.19	3.9	1.94
14.70	75	57.62	78	2.96	28.58	10.4	3.47
14.72	75	54.41	79	4.99	30.38	16.4	5.37
14.75	76	55.87	78	7.98	32.80	24.3	7.58
14.74	77	54.83	77	9.95	34.84	28.6	9.01
14.76	77	55.34	78	11.98	36.19	33.1	10.16

MS1GG

STANDARD PERFORMANCE TEST AT 10.0 PSIA AND 75 F NOMINAL

WASTE PRES (PSIA)	AVG BED TEMP (F)	BED INLET PRES (PSID)	BED INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
9.96	77	15.21	79	0.12	8.29	1.4	1.30
10.33	77	15.07	78	0.50	8.60	5.8	2.54
10.04	76	15.41	78	1.06	9.28	11.4	4.38
10.00	77	15.68	84	2.06	10.05	20.5	7.84
10.00	78	15.35	81	2.99	10.68	28.0	10.93
10.08	72	20.11	79	0.12	10.86	1.1	0.98
10.07	71	20.10	78	0.49	11.19	4.4	1.57
10.05	72	19.91	79	1.03	11.57	8.9	2.96
10.03	72	19.98	78	1.99	12.46	16.0	5.65
10.07	72	20.16	79	2.97	13.27	22.4	8.14
10.05	70	19.80	78	3.96	13.85	28.6	10.07
10.08	71	20.24	79	5.00	15.08	33.2	11.91
10.00	80	25.29	81	0.11	12.78	0.9	0.93
9.99	80	25.87	80	0.97	14.00	6.9	2.38
10.01	78	25.28	81	3.03	15.44	19.6	6.43
9.99	78	25.73	78	5.02	17.18	29.2	9.75
10.00	77	25.51	79	8.01	19.42	41.2	12.93
10.03	74	30.17	81	0.11	15.31	0.7	0.94
10.02	74	29.88	78	1.02	15.94	6.4	2.09
9.99	74	29.34	78	3.03	17.50	17.3	5.41
9.95	76	30.58	85	5.05	19.77	25.5	8.49
9.99	77	30.17	81	8.04	22.24	36.2	11.69
10.00	79	40.03	81	0.10	19.56	0.5	1.07
10.03	80	40.61	79	1.00	20.62	4.8	1.81
10.00	79	40.79	78	2.98	22.26	13.4	4.00
10.01	78	40.42	78	5.03	24.02	20.9	6.32
10.04	78	40.75	80	8.00	26.26	30.5	9.09
10.01	77	40.27	77	10.14	27.45	36.9	10.77
9.99	76	40.54	79	12.01	29.17	41.2	11.88
10.05	77	55.19	78	0.13	25.67	0.5	1.32
10.05	75	55.42	55	0.98	26.54	3.7	1.76
10.03	72	55.52	49	3.00	28.49	10.5	3.24
9.99	72	55.16	77	5.10	30.26	16.9	5.00
9.96	74	55.18	78	8.05	32.54	24.7	7.23
9.99	76	55.21	78	10.05	34.17	29.4	8.56
10.00	76	54.75	77	12.01	35.53	33.8	9.78

MSIGG

STANDARD PERFORMANCE TEST AT 6.0 PSIA AND 75 F NOMINAL

WASTE PRES (PSIA)	AVG BED TEMP (F)	BED INLET PRES (PSID)	BED INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
6.00	73	15.66	78	0.10	8.12	1.2	1.10
5.93	72	15.46	79	0.51	8.36	6.1	1.88
5.97	73	15.70	77	1.08	8.98	12.0	3.37
6.08	72	15.13	81	2.04	9.55	21.4	6.58
5.99	73	15.85	78	3.06	10.65	28.7	9.42
6.06	72	19.91	81	0.09	10.09	0.9	0.92
6.07	72	20.05	80	0.51	10.63	4.8	1.46
6.05	72	20.15	81	1.02	11.20	9.1	2.37
6.05	72	19.89	80	2.02	11.82	17.1	4.56
6.05	73	19.93	80	3.03	12.84	23.6	7.12
6.06	73	20.30	80	3.99	13.57	29.4	9.24
6.07	74	20.12	78	5.05	14.27	35.4	10.90
6.07	77	25.52	84	0.11	12.64	0.9	0.93
6.00	77	25.24	80	0.98	13.35	7.3	2.04
6.00	74	25.47	79	3.06	15.25	20.1	5.68
6.00	75	25.29	80	5.05	16.68	30.3	8.90
6.00	75	25.49	77	8.02	18.67	43.0	12.28
6.03	75	29.72	80	0.12	14.44	0.8	0.92
6.02	77	30.42	79	1.01	15.59	6.5	1.82
6.03	76	30.30	80	2.97	17.37	17.1	4.69
6.03	75	30.26	78	5.06	18.74	27.0	7.68
6.02	77	30.41	79	8.06	21.33	37.8	11.03
6.06	80	40.27	78	0.11	18.84	0.6	1.03
6.05	80	40.62	77	1.05	20.13	5.2	1.76
6.04	79	40.66	75	3.00	21.85	13.7	3.76
6.03	79	40.40	80	5.05	23.73	21.3	6.17
6.04	76	40.74	78	10.00	27.37	36.5	10.30
6.03	76	40.75	78	11.96	28.44	42.1	11.58
6.04	82	55.07	79	0.12	24.77	0.5	1.24
6.06	81	55.14	79	1.02	25.82	4.0	1.73
5.98	74	55.80	66	3.04	28.26	10.8	3.25
5.98	73	55.29	63	5.11	29.46	17.3	4.83
5.99	72	54.79	75	7.96	31.96	24.9	6.93
5.97	74	55.18	80	9.96	33.50	29.7	8.31
5.97	71	54.90	78	12.10	35.18	34.4	9.41

MSIGG

STANDARD PERFORMANCE TEST AT 3.0 PSIA AND 75 F NOMINAL

WASTE PRES (PSIA)	AVG BED TEMP (F)	BED INLET PRES (PSID)	BED INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
2.99	73	15.27	82	0.10	7.45	1.3	1.02
2.99	71	15.32	81	0.51	7.87	6.5	1.53
2.99	70	15.52	78	1.03	8.37	12.3	2.79
3.01	73	15.57	80	1.96	9.03	21.7	5.81
2.96	69	20.51	78	0.11	9.78	1.1	0.84
3.03	70	20.16	79	0.51	10.09	5.1	1.27
3.03	70	20.17	80	1.06	10.55	10.0	2.20
3.04	69	19.85	79	1.99	11.17	17.8	4.07
3.03	69	20.33	80	2.97	12.15	24.4	6.43
3.05	68	20.06	77	4.01	12.84	31.2	8.43
2.97	79	25.63	83	0.11	11.96	0.9	0.91
2.98	79	25.80	80	1.00	12.89	7.8	1.94
2.97	76	25.19	78	2.91	14.17	20.5	5.22
2.96	77	25.77	80	5.00	16.23	30.8	8.55
2.97	76	25.42	78	8.01	18.09	44.3	11.90
3.02	72	29.95	78	0.12	13.97	0.9	0.90
3.02	73	30.15	80	1.01	14.87	6.8	1.65
3.03	73	30.39	79	2.98	16.71	17.8	4.43
3.02	73	30.01	78	5.03	18.05	27.9	7.51
3.03	74	30.40	80	8.02	20.35	39.4	10.66
3.05	80	40.07	78	0.11	17.93	0.6	0.96
3.09	81	40.48	79	1.00	19.14	5.2	1.59
3.10	79	40.72	81	3.01	21.08	14.3	3.63
3.02	79	40.81	80	5.01	22.47	22.3	5.90
3.02	78	40.88	76	8.01	24.66	32.5	8.66
3.03	79	40.42	76	9.94	26.00	38.2	10.31
3.02	78	40.18	76	12.11	27.54	44.0	11.78
4.07	78	55.13	80	0.12	24.52	0.5	1.26
4.10	78	55.47	78	1.01	25.77	3.9	1.70
4.13	78	55.62	76	3.00	27.27	11.0	3.18
4.09	78	55.48	79	5.02	28.69	17.5	4.86
4.09	77	55.76	78	7.99	31.16	25.6	6.96
3.99	79	55.72	79	10.09	33.16	30.4	8.34
4.02	79	55.30	78	11.98	34.53	34.7	9.58

MSIGG

STANDARD PERFORMANCE TEST AT SEA LEVEL AND 40 F NOMINAL

WASTE PRES (PSIA)	AVG BED TEMP (F)	BED INLET PRES (PSID)	BED INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
14.77	39	19.93	43	0.11	10.94	1.0	1.11
14.77	38	20.24	44	1.01	12.03	8.4	3.18
14.74	38	19.88	42	2.07	12.85	16.1	6.46
14.77	37	19.98	45	3.05	13.77	22.1	8.95
14.76	37	19.70	43	4.09	14.56	28.1	11.07
14.71	41	29.82	42	0.11	15.62	0.7	1.10
14.69	40	29.80	41	1.00	16.55	6.0	2.19
14.71	39	30.05	42	2.05	17.63	11.6	3.92
14.70	39	30.01	42	3.04	18.56	16.4	5.50
14.69	39	29.73	41	3.95	19.16	20.6	7.40
14.70	38	29.71	40	6.01	21.13	28.4	9.62
14.67	40	39.83	41	0.11	20.17	0.5	1.36
14.68	40	40.00	40	1.01	21.34	4.7	1.91
14.70	40	39.92	41	2.06	22.11	9.3	3.13
14.71	41	40.12	42	3.09	22.87	13.5	4.20
14.69	40	40.24	41	4.99	25.06	19.9	6.57
14.69	39	40.29	41	6.99	26.28	26.6	8.38
14.71	39	39.88	40	8.96	28.30	31.7	10.01
14.67	40	50.26	38	0.11	24.33	0.5	1.34
14.70	41	50.01	39	1.02	25.33	4.0	1.90
14.67	40	49.76	39	3.03	27.17	11.2	3.51
14.69	39	50.17	39	5.00	29.36	17.0	5.32
14.67	38	50.03	38	6.98	30.75	22.7	6.88
14.67	37	50.16	37	8.97	32.60	27.5	8.25
14.70	38	50.01	42	11.00	34.28	32.1	9.56

MSIGG

STANDARD PERFORMANCE TEST AT SEA LEVEL AND 110 F NOMINAL

WASTE PRES (PSIA)	AVG BED TEMP (F)	BED INLET PRES (PSID)	BED INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
13.70	108	20.73	112	0.10	10.89	0.9	1.41
13.70	107	20.76	109	0.98	11.88	8.2	4.29
13.70	107	20.80	111	2.02	12.56	16.1	7.34
13.70	107	20.93	112	3.00	13.64	22.0	10.18
13.75	106	20.99	112	4.03	14.57	27.7	12.11
13.75	107	31.02	113	0.10	15.72	0.6	2.01
14.20	109	30.50	108	1.03	16.28	6.3	3.00
14.25	108	30.79	106	1.99	17.27	11.5	5.07
14.20	108	30.56	105	2.98	18.22	16.4	6.99
14.25	107	30.21	106	3.99	18.98	21.0	8.92
14.20	107	30.63	104	5.06	20.17	25.1	10.46
14.20	108	40.62	107	0.11	19.83	0.6	1.60
14.20	109	40.14	107	1.01	20.40	5.0	2.44
14.20	109	40.75	108	1.99	21.60	9.2	3.93
14.20	107	40.38	105	3.00	22.41	13.4	5.48
14.20	106	40.46	109	5.02	24.20	20.7	8.16
14.20	105	40.47	110	7.07	25.91	27.3	10.35
14.20	108	50.99	111	0.11	24.17	0.5	1.99
14.20	108	50.58	111	1.03	25.37	4.1	2.44
14.20	106	50.50	111	2.98	26.84	11.1	4.60
14.20	107	50.00	111	5.12	28.19	18.2	6.68
14.20	107	50.70	111	7.10	30.25	23.5	8.75
14.20	108	50.62	112	9.05	31.91	28.4	10.18

MSIGG

STANDARD PERFORMANCE TEST AT SEA LEVEL AND 150 F NOMINAL

WASTE PRES (PSIA)	AVG BED TEMP (F)	BED INLET PRES (PSID)	BED INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
14.45	146	20.17	151	0.10	10.26	1.0	2.10
14.40	146	20.51	155	1.03	11.19	9.2	5.48
14.40	145	20.31	154	2.00	11.92	16.8	9.47
14.45	146	20.46	157	2.97	12.86	23.1	11.60
14.45	145	20.05	155	4.06	13.63	29.8	13.83
14.42	146	30.14	156	0.10	14.51	0.7	1.91
14.37	144	30.33	157	1.04	15.52	6.7	3.85
14.42	146	30.01	155	1.98	16.22	12.2	6.46
14.45	146	30.21	155	3.01	17.12	17.6	8.39
14.40	146	30.42	157	3.96	18.06	21.9	10.36
14.40	147	30.00	157	5.02	18.81	26.7	11.73
14.38	148	40.58	158	0.10	18.79	0.5	2.04
14.37	146	40.24	155	1.07	19.57	5.5	3.34
14.38	145	39.89	153	2.04	20.39	10.0	5.02
14.37	145	40.07	156	2.96	21.07	14.0	6.56
14.35	147	40.18	157	5.04	22.91	22.0	9.56
14.37	147	39.95	156	7.13	24.29	29.4	11.86
14.30	146	48.56	148	6.84	27.95	24.5	10.34
13.95	146	48.92	149	9.03	29.99	30.1	12.24

APPENDIX G

PMIGG Steady State Performance Data

PMIGG

STANDARD PERFORMANCE TEST AT SEA LEVEL AND 75 F NOMINAL

WASTE PRES (PSIA)	AVG MODULE TEMP (F)	MODULE INLET PRES (PSID)	MODULE INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
14.71	73	29.53	78	0.11	1.91	5.8	4.64
14.71	74	30.24	77	0.80	2.73	29.3	8.69
14.71	74	30.16	76	1.50	3.45	43.5	11.69
14.70	73	49.85	76	0.73	3.86	18.9	5.18
14.71	73	49.81	76	1.50	4.71	31.8	7.67
14.71	74	49.88	76	2.55	5.72	44.6	10.07
14.70	73	49.48	76	4.00	7.26	55.1	12.49
14.69	73	69.79	76	0.76	5.09	14.9	3.86
14.70	73	69.65	76	1.50	5.87	25.6	5.48
14.72	73	69.49	77	2.54	6.93	36.7	7.58
14.71	73	70.23	77	4.06	8.60	47.2	9.78
14.73	73	69.80	77	6.06	10.58	57.3	11.90
14.68	73	84.65	76	0.79	5.93	13.3	3.26
14.70	73	84.55	76	1.46	6.66	21.9	4.41
14.66	73	84.46	76	2.55	7.89	32.3	6.35
14.74	73	84.81	76	3.96	9.43	42.0	8.28
14.69	73	84.81	77	6.04	11.47	52.7	10.42
14.70	73	99.88	77	0.75	6.77	11.1	3.08
14.70	73	100.14	77	1.47	7.62	19.3	3.92
14.70	73	100.02	77	2.45	8.63	28.2	5.30
14.71	73	100.17	77	4.16	10.50	39.6	7.42
14.71	73	99.99	77	6.11	12.59	48.5	9.27

PMIGG

STANDARD PERFORMANCE TEST AT 10.0 PSIA AND 75 F NOMINAL

WASTE PRES (PSIA)	AVG MODULE TEMP (F)	MODULE INLET PRES (PSID)	MODULE INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
10.04	77	29.72	70	0.78	2.81	27.8	8.45
10.02	76	30.40	72	1.05	3.05	34.4	9.48
10.01	75	30.19	74	1.55	3.57	43.4	11.42
10.03	73	50.16	76	0.72	3.99	18.0	5.42
9.99	72	49.98	77	1.50	4.76	31.5	7.61
10.03	72	49.72	82	2.54	5.85	43.4	9.90
10.02	72	49.58	84	3.94	7.25	54.3	12.10
9.98	72	70.08	84	0.72	5.29	13.6	4.03
10.02	74	69.87	85	1.54	6.18	24.9	5.54
9.98	74	69.78	86	2.51	7.27	34.5	7.21
9.99	75	69.62	87	3.98	8.82	45.1	9.43
10.03	76	70.19	80	5.97	10.94	54.6	11.48
10.09	73	85.36	84	0.76	6.28	12.1	3.33
9.99	73	85.38	86	1.46	7.18	20.3	4.46
9.99	76	85.21	86	2.56	8.49	30.2	6.14
10.01	76	85.05	80	4.03	10.01	40.3	8.17
10.00	75	84.77	80	6.08	12.01	50.6	10.27
10.01	73	100.44	83	0.70	7.20	9.7	3.18
10.01	73	100.25	84	1.55	8.16	19.0	4.16
10.03	75	100.17	85	2.43	9.32	26.1	5.25
10.01	75	100.00	80	3.93	10.78	36.5	7.13
10.05	73	99.75	76	5.99	12.64	47.4	9.20

PMIGG

STANDARD PERFORMANCE TEST AT 6.0 PSIA AND 75 F NOMINAL

WASTE PRES (PSIA)	AVG MODULE TEMP (F)	MODULE INLET PRES (PSID)	MODULE INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
6.02	71	30.38	76	0.77	2.59	29.7	7.65
6.00	71	30.37	77	1.06	2.88	36.8	8.97
6.01	71	30.25	79	1.60	3.43	46.6	10.98
6.01	71	49.90	82	0.75	3.76	19.9	4.94
6.00	71	49.75	83	1.54	4.66	33.0	7.23
6.01	71	49.61	84	2.52	5.64	44.7	9.45
6.01	73	50.20	91	4.09	7.45	54.9	11.70
6.02	76	69.93	86	0.74	5.67	13.1	3.49
6.01	77	69.82	79	1.52	6.41	23.7	5.08
6.01	77	69.70	74	2.53	7.37	34.3	7.09
6.01	75	69.54	68	3.97	8.70	45.6	9.39
6.01	70	70.01	67	6.16	10.50	58.7	11.86
6.00	73	85.40	89	0.75	6.45	11.6	3.23
6.01	74	85.05	81	1.52	7.23	21.0	4.37
6.01	74	84.90	79	2.53	8.22	30.8	5.99
6.01	73	84.76	79	4.13	9.79	42.2	8.21
6.01	73	84.44	79	6.06	11.67	51.9	10.15
6.01	72	99.74	82	0.81	7.08	11.4	3.01
6.02	72	99.66	86	1.57	7.98	19.7	4.07
6.02	73	99.48	90	2.54	9.19	27.6	5.25
6.03	74	99.18	92	4.06	10.94	37.1	6.97
6.02	78	99.63	79	5.96	13.17	45.3	8.75

PMIGG

STANDARD PERFORMANCE TEST AT 3.0 PSIA AND 75 F NOMINAL

WASTE PRES (PSIA)	AVG MODULE TEMP (F)	MODULE INLET PRES (PSID)	MODULE INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
2.99	75	29.90	76	0.74	2.58	28.7	7.17
2.99	74	29.83	76	1.00	2.82	35.5	8.44
2.99	74	30.12	76	1.49	3.30	45.2	10.28
2.99	73	49.61	76	0.75	3.83	19.6	4.82
2.99	73	49.56	76	1.47	4.58	32.1	6.97
2.99	73	49.94	78	2.50	5.62	44.5	9.30
2.98	72	49.53	80	4.08	7.21	56.6	11.88
2.99	71	70.29	84	0.74	5.05	14.7	3.87
2.99	72	70.24	87	1.49	5.85	25.5	5.22
2.99	73	70.01	91	2.52	7.14	35.3	7.01
2.99	74	69.83	92	3.99	8.72	45.8	9.09
2.98	78	69.81	74	6.02	10.85	55.5	11.35
2.99	73	84.69	76	0.76	6.10	12.5	3.43
2.98	72	84.60	77	1.50	6.79	22.1	4.65
2.99	72	84.50	78	2.50	7.82	32.0	6.19
2.99	72	85.14	81	4.12	9.67	42.6	8.22
2.99	72	84.79	89	6.07	11.69	51.9	10.08
2.99	73	100.54	91	0.78	7.19	10.8	3.12
2.99	74	100.37	93	1.51	8.06	18.7	3.87
2.99	75	100.19	93	2.56	9.37	27.3	5.19
2.98	77	100.02	81	4.04	11.02	36.7	6.91
2.98	73	99.91	66	6.19	12.38	50.0	9.46

PMIGG

STANDARD PERFORMANCE TEST AT SEA LEVEL AND 30 F NOMINAL

WASTE PRES (PSIA)	AVG MODULE TEMP (F)	MODULE INLET PRES (PSID)	MODULE INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
14.68	31	50.08	25	1.51	3.25	46.5	9.38
14.67	32	50.04	26	2.45	4.23	57.9	11.82
14.68	32	49.79	25	3.96	5.71	69.4	14.17
14.68	30	69.87	25	1.46	3.82	38.2	6.67
14.68	30	70.69	25	2.50	4.98	50.2	9.12
14.67	30	70.67	25	4.02	6.53	61.6	11.63
14.67	30	85.25	25	1.48	4.37	33.9	5.46
14.68	30	85.17	25	2.49	5.45	45.7	7.69
14.68	30	85.18	24	4.02	7.02	57.3	10.17
14.67	30	100.66	25	1.47	4.95	29.7	4.60
14.69	29	100.58	26	2.52	6.12	41.2	6.70
14.68	29	100.58	27	3.98	7.73	51.5	9.00
14.68	29	100.17	26	8.24	11.99	68.7	12.88

PMIGG
STANDARD PERFORMANCE TEST AT SEA LEVEL AND 45 F NOMINAL

WASTE PRES (PSIA)	AVG MODULE TEMP (F)	MODULE INLET PRES (PSID)	MODULE INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
14.68	47	30.51	46	1.48	2.83	52.3	12.82
14.67	47	50.07	44	4.00	6.27	63.8	13.56
14.68	47	69.99	45	1.52	4.56	33.3	6.39
14.68	47	69.89	46	2.52	5.62	44.8	8.64
14.68	47	69.68	46	4.02	7.16	56.1	11.03
14.68	46	85.13	45	1.47	5.12	28.7	5.12
14.67	46	85.03	45	2.49	6.13	40.6	7.13
14.67	46	84.76	46	4.03	7.77	51.9	9.51
14.67	46	84.82	45	8.27	12.17	68.0	13.36
14.67	47	99.87	44	1.51	5.73	26.4	4.36
14.68	46	99.72	44	2.54	6.82	37.2	6.17
14.68	46	99.60	45	3.99	8.37	47.7	8.32

PMIGG (MFGR'D JULY 84)

STANDARD PERFORMANCE TEST AT SEA LEVEL AND 75 F NOMINAL

WASTE PRES (PSIA)	AVG MODULE TEMP (F)	MODULE INLET PRES (PSID)	MODULE INLET TEMP (F)	PROD FLOW (PPM)	INLET FLOW (PPM)	O/I (%)	PROD OXYGEN (%)
14.30	73	30.50	74	0.24	1.88	12.8	6.37
14.30	74	30.21	74	0.74	2.30	32.2	9.56
14.31	74	30.25	75	1.50	3.08	48.7	12.94
14.32	75	49.90	76	0.26	2.84	9.2	4.29
14.32	74	50.11	74	0.76	3.37	22.6	5.80
14.32	74	50.20	75	1.48	4.15	35.7	8.43
14.31	73	50.07	75	2.52	5.16	48.8	11.11
14.30	74	50.40	75	4.00	6.75	59.3	13.39
14.32	75	70.23	75	0.29	3.99	7.3	3.39
14.32	75	69.99	77	0.75	4.51	16.6	3.94
14.43	75	70.13	76	1.51	5.24	28.8	5.96
14.43	75	69.96	75	2.50	6.22	40.2	8.39
14.42	75	69.98	75	3.99	7.76	51.5	10.92
14.41	75	70.12	76	6.03	9.77	61.7	13.07
14.43	75	85.30	76	0.35	4.64	7.5	2.92
14.44	75	85.00	76	0.75	5.03	14.9	3.20
14.43	74	85.30	75	1.52	5.97	25.5	4.78
14.44	74	85.00	75	2.49	7.04	35.4	6.83
14.43	73	85.60	75	3.99	8.64	46.2	9.33
14.43	73	84.90	75	6.00	10.53	57.0	11.66
14.30	74	99.90	75	0.38	5.45	7.0	2.60
14.29	74	100.30	75	0.75	5.87	12.8	2.75
14.29	74	99.90	76	1.49	6.91	21.6	3.57
14.29	74	99.90	75	2.52	7.90	31.9	5.72
14.28	74	99.90	75	4.02	9.46	42.5	8.02
14.28	74	100.30	76	5.98	11.71	51.1	10.25

APPENDIX H

MSIGG Detailed Mission Simulation Data Plots

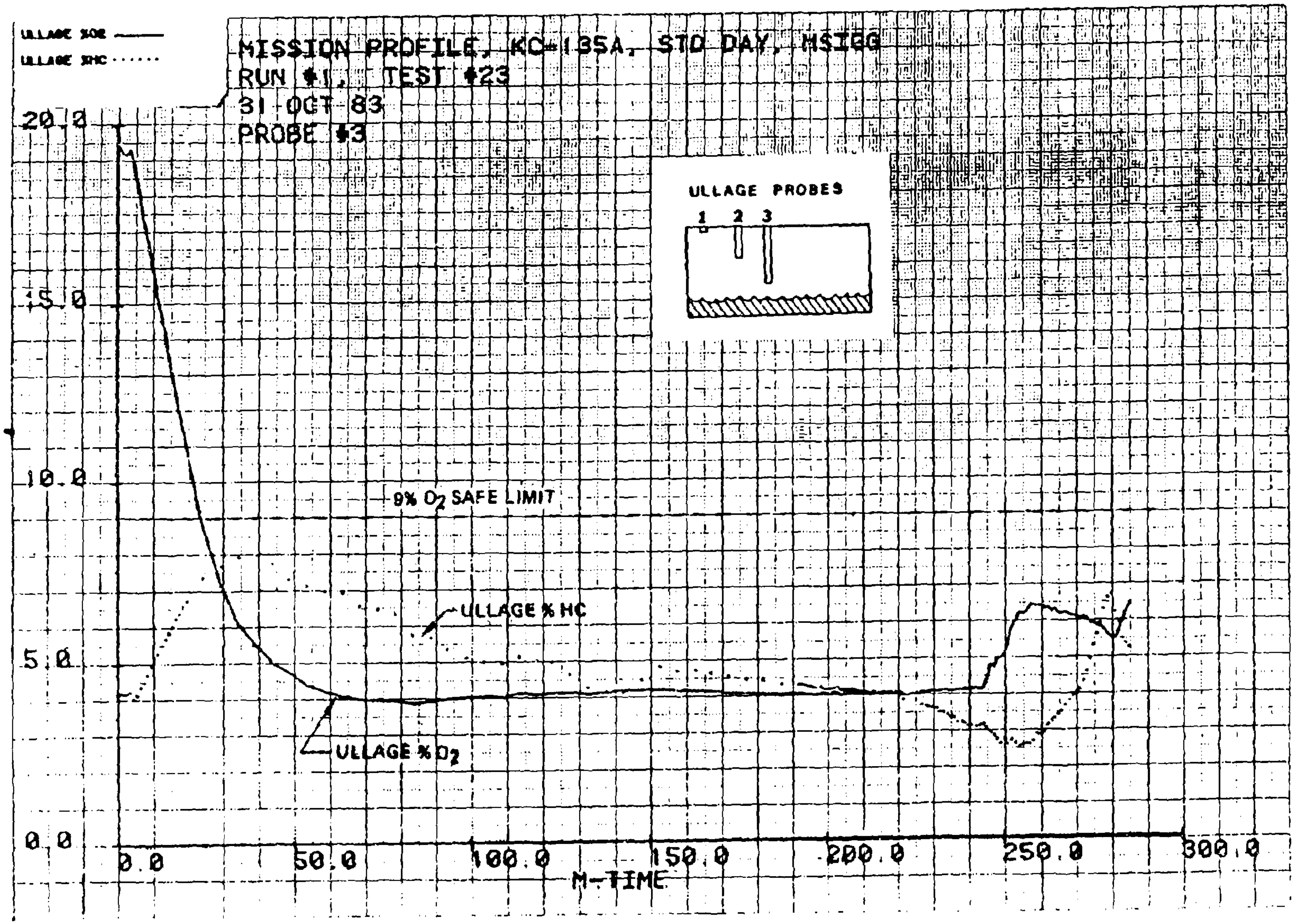

ULLAGE %O2
ULLAGE %HC
MISSION PROFILE, KC-135A, STD DAY, MSIGG
RUN #1, TEST #23
31 OCT 83
PROBE #3
ULLAGE PROBES
1 2 3
20.0
15.0
10.0
5.0
0.0
9% O2 SAFE LIMIT
ULLAGE % HC
ULLAGE % O2
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
8408:8-24

Figure H-1.

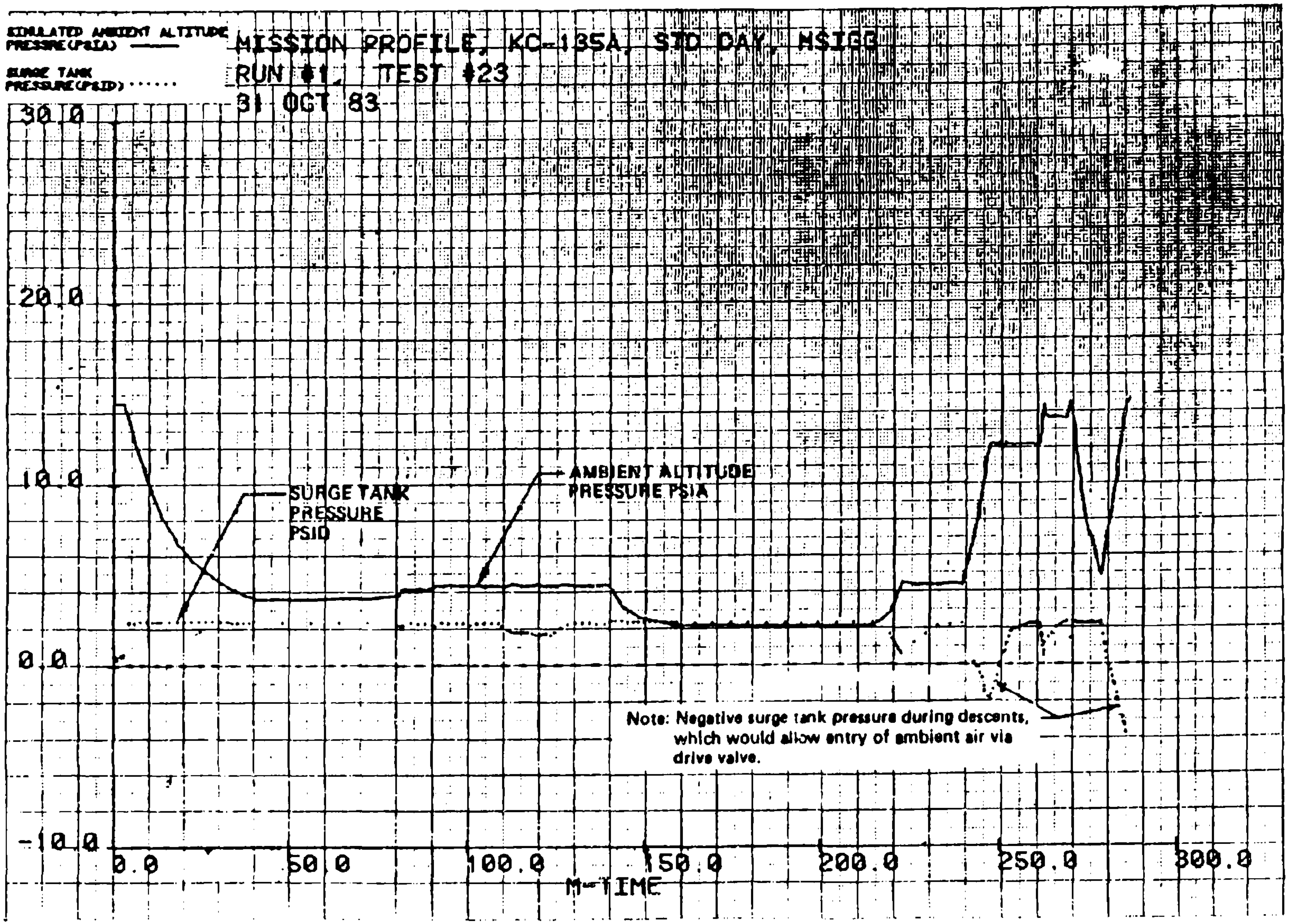
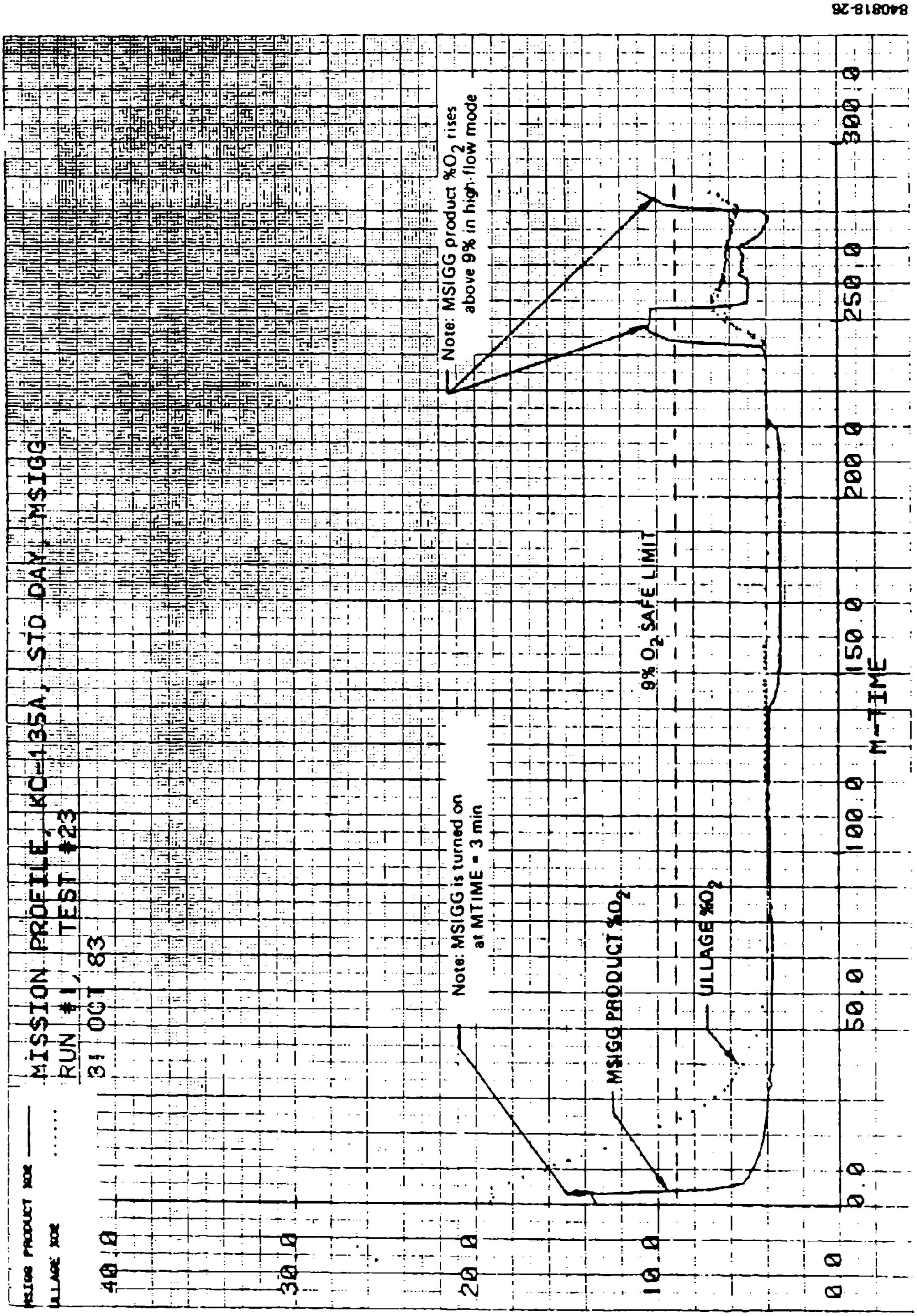

SIMULATED AMBIENT ALTITUDE PRESSURE (PSIA)
SURGE TANK PRESSURE (PSID)
MISSION PROFILE, KC-135A, STD DAY, MSIGG
RUN #1, TEST #23
31 OCT 83
30.0
20.0
10.0
0.0
-10.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
SURGE TANK PRESSURE PSID
AMBIENT ALTITUDE PRESSURE PSIA
Note: Negative surge tank pressure during descents, which would allow entry of ambient air via drive valve.
840818-25

Figure H-2.



MSIGG PRODUCT %O2
ULLAGE %O2
MISSION PROFILE, KC-135A, STD DAY, MSIGG
RUN #1, TEST #23
31 OCT 83
40.0
30.0
20.0
10.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
Note: MSIGG is turned on at MTIME = 3 min
MSIGG PRODUCT %O2
ULLAGE %O2
9% O2 SAFE LIMIT
Note: MSIGG product %O2 rises above 9% in high flow mode
840818-26

Figure H-3.

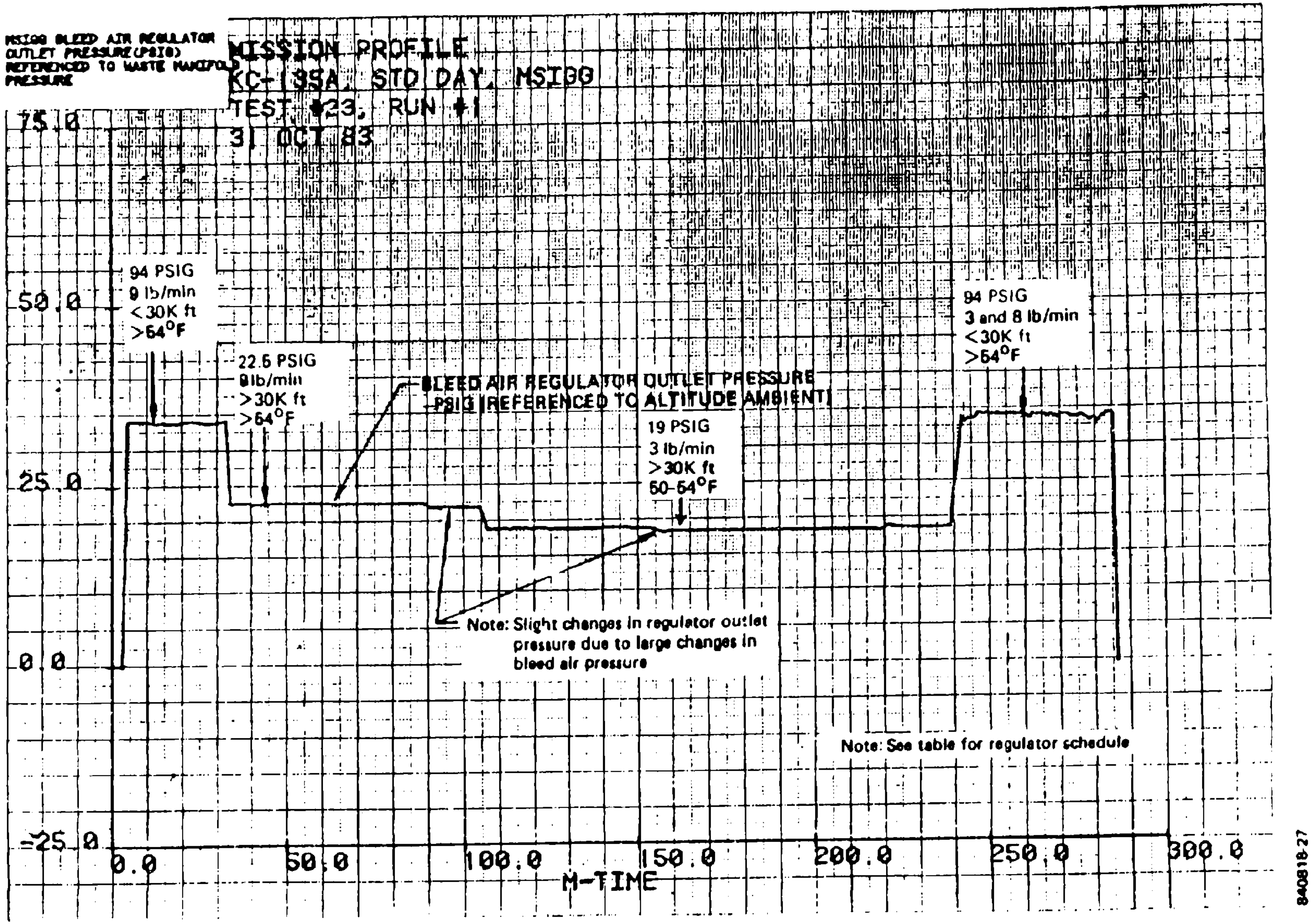
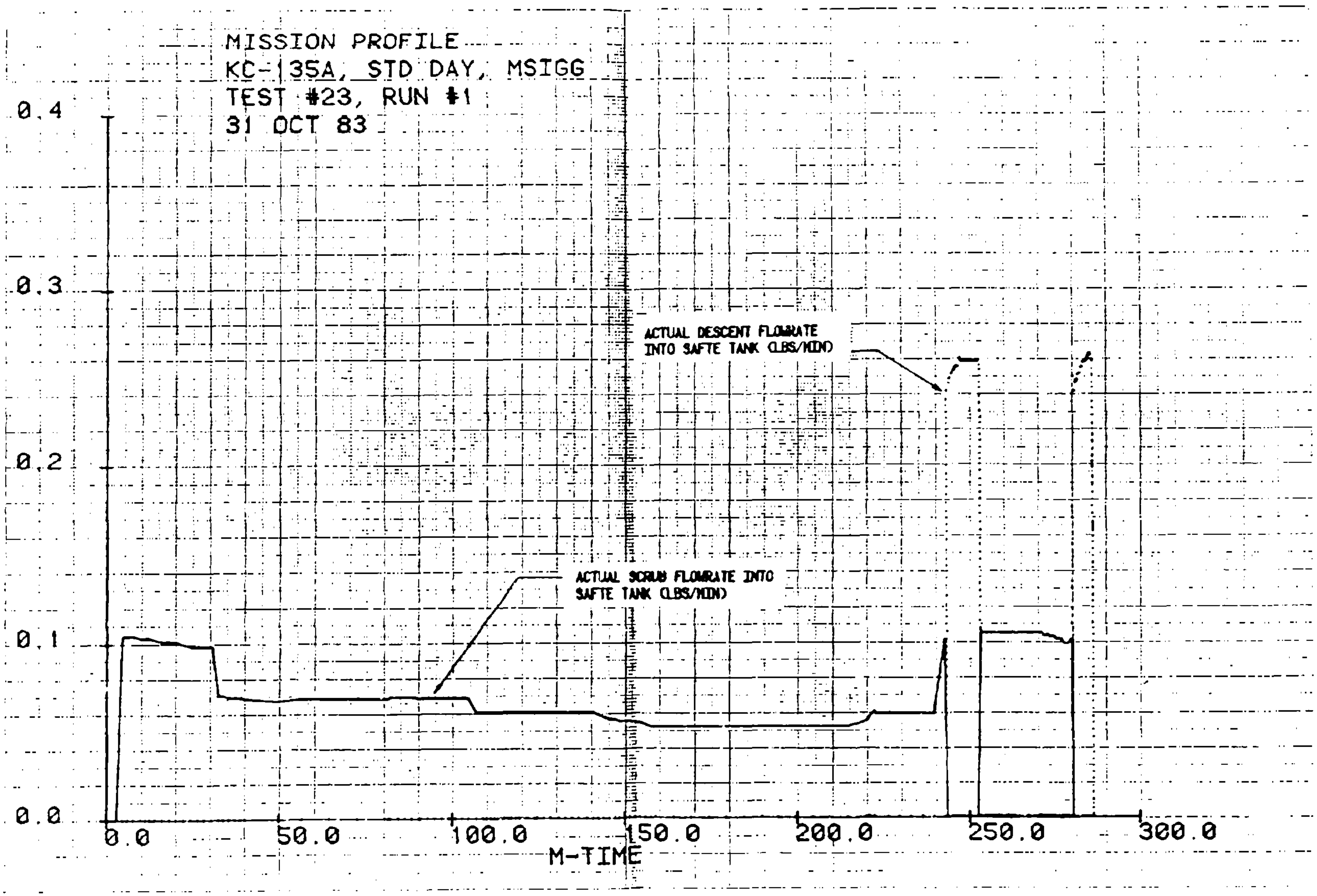

MSIGG BLEED AIR REGULATOR OUTLET PRESSURE (PSIG) REFERENCED TO WASTE MANIFOLD PRESSURE
MISSION PROFILE
KC-135A, STD DAY, MSIGG
TEST #23, RUN #1
31 OCT 83
75.0
50.0
25.0
0.0
-25.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
94 PSIG
9 lb/min
<30K ft
>64°F
22.5 PSIG
9 lb/min
>30K ft
>64°F
BLEED AIR REGULATOR OUTLET PRESSURE
PSIG (REFERENCED TO ALTITUDE AMBIENT)
19 PSIG
3 lb/min
>30K ft
50-64°F
94 PSIG
3 and 8 lb/min
<30K ft
>64°F
Note: Slight changes in regulator outlet pressure due to large changes in bleed air pressure
Note: See table for regulator schedule
840818-27

Figure H-4.



MISSION PROFILE
KC-135A, STD DAY, MSIGG
TEST #23, RUN #1
31 OCT 83
0.4
0.3
0.2
0.1
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
ACTUAL DESCENT FLOWRATE INTO SAFTE TANK (LBS/MIN)
ACTUAL SCRUB FLOWRATE INTO SAFTE TANK (LBS/MIN)

Figure H-5.

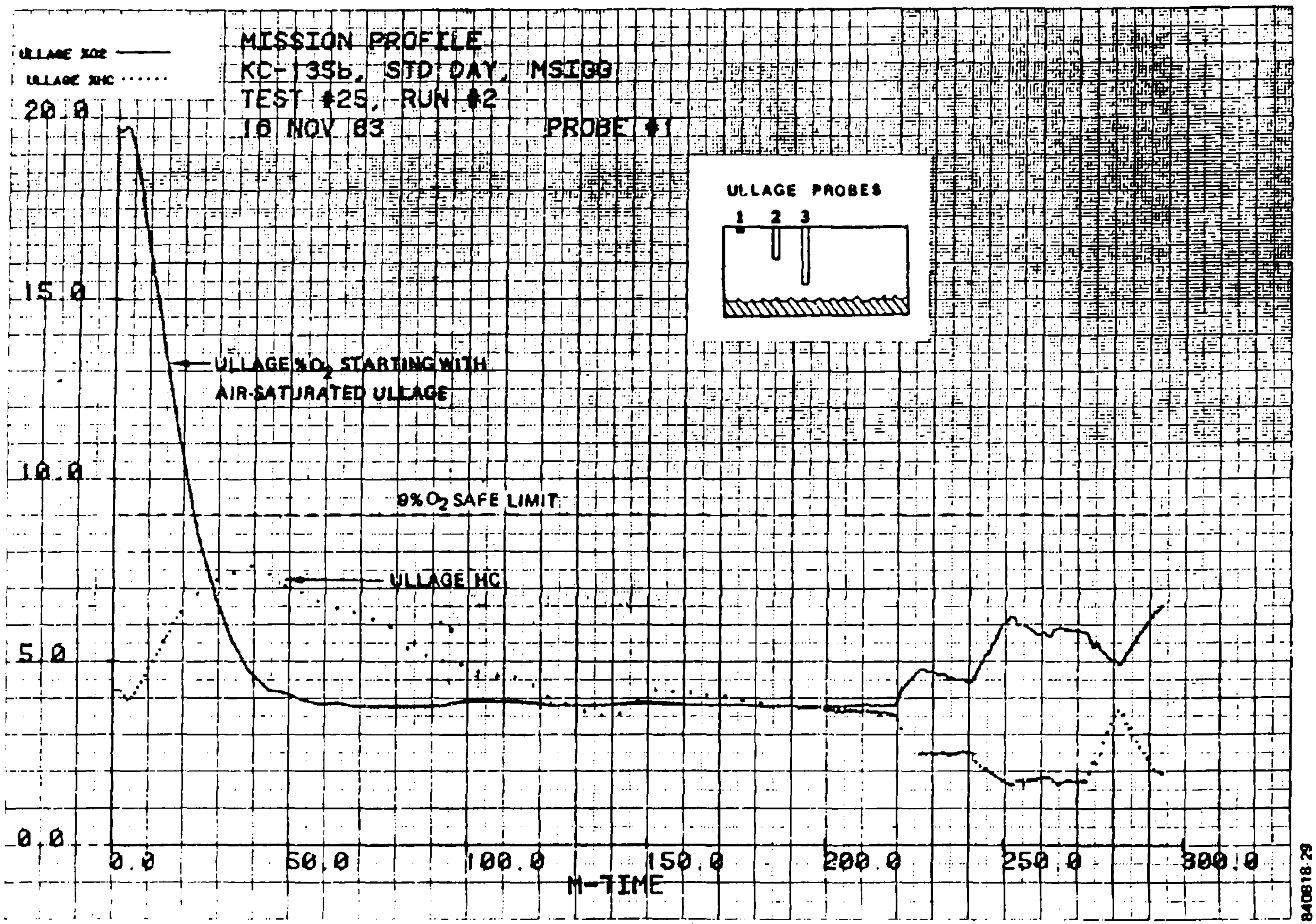

ULLAGE %O2
ULLAGE %HC
MISSION PROFILE
KC-135b, STD DAY, MSIGG
TEST #25, RUN #2
16 NOV 83
PROBE #1
ULLAGE PROBES
1 2 3
ULLAGE %O2 STARTING WITH AIR-SATURATED ULLAGE
9% O2 SAFE LIMIT
ULLAGE HC
20.0
15.0
10.0
5.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
840818-29

Figure H-6.

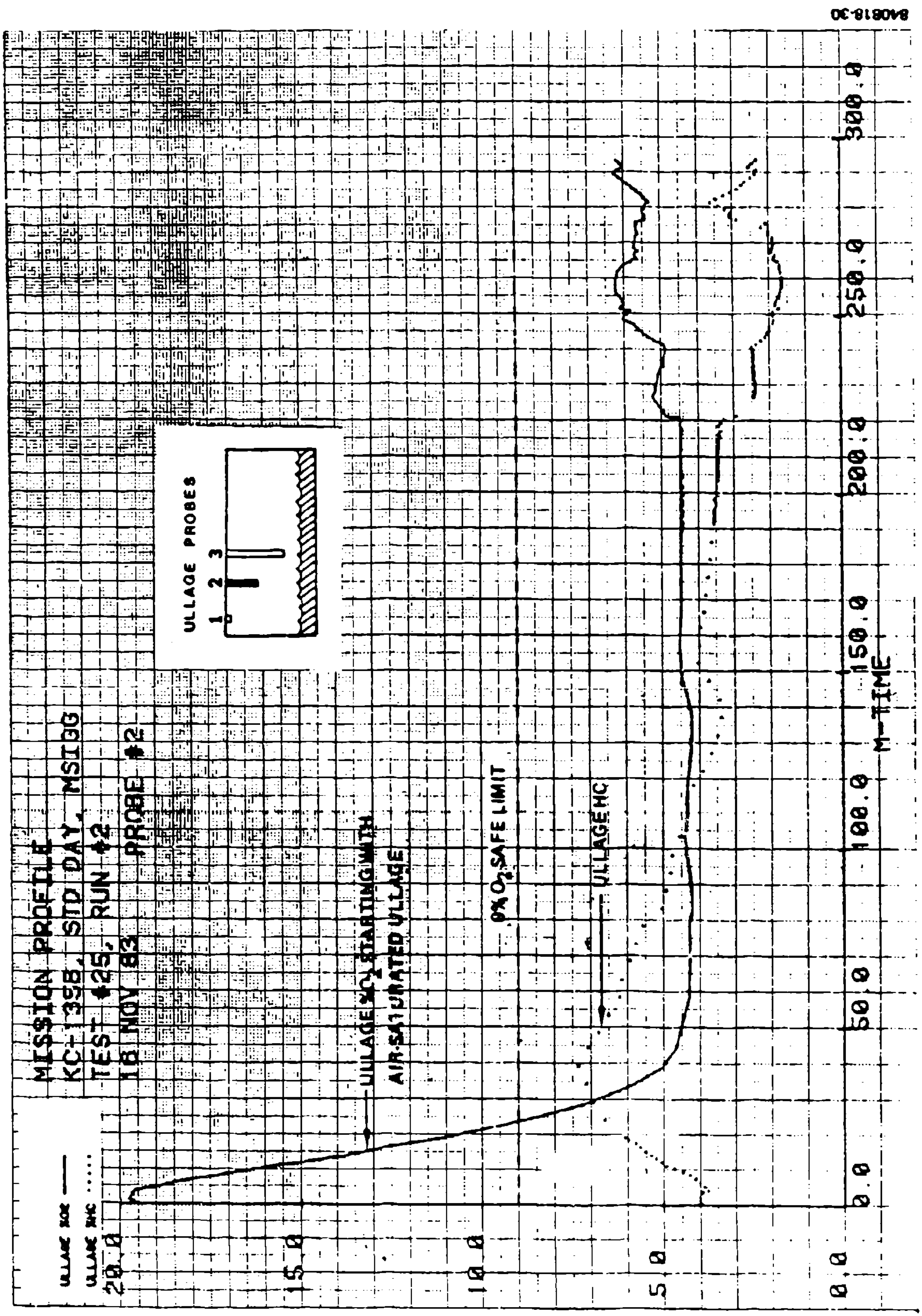

840818-30
MISSION PROFILE
KC-135B, STD DAY, MSIGG
TEST #25, RUN #2
18 NOV 83 PROBE #2
ULLAGE %O2
ULLAGE %HC
ULLAGE %O2 STARTING WITH
AIR-SATURATED ULLAGE
9% O2 SAFE LIMIT
ULLAGE HC
ULLAGE PROBES
1 2 3
20.0
15.0
10.0
5.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME

Figure H-7.

840E18-31

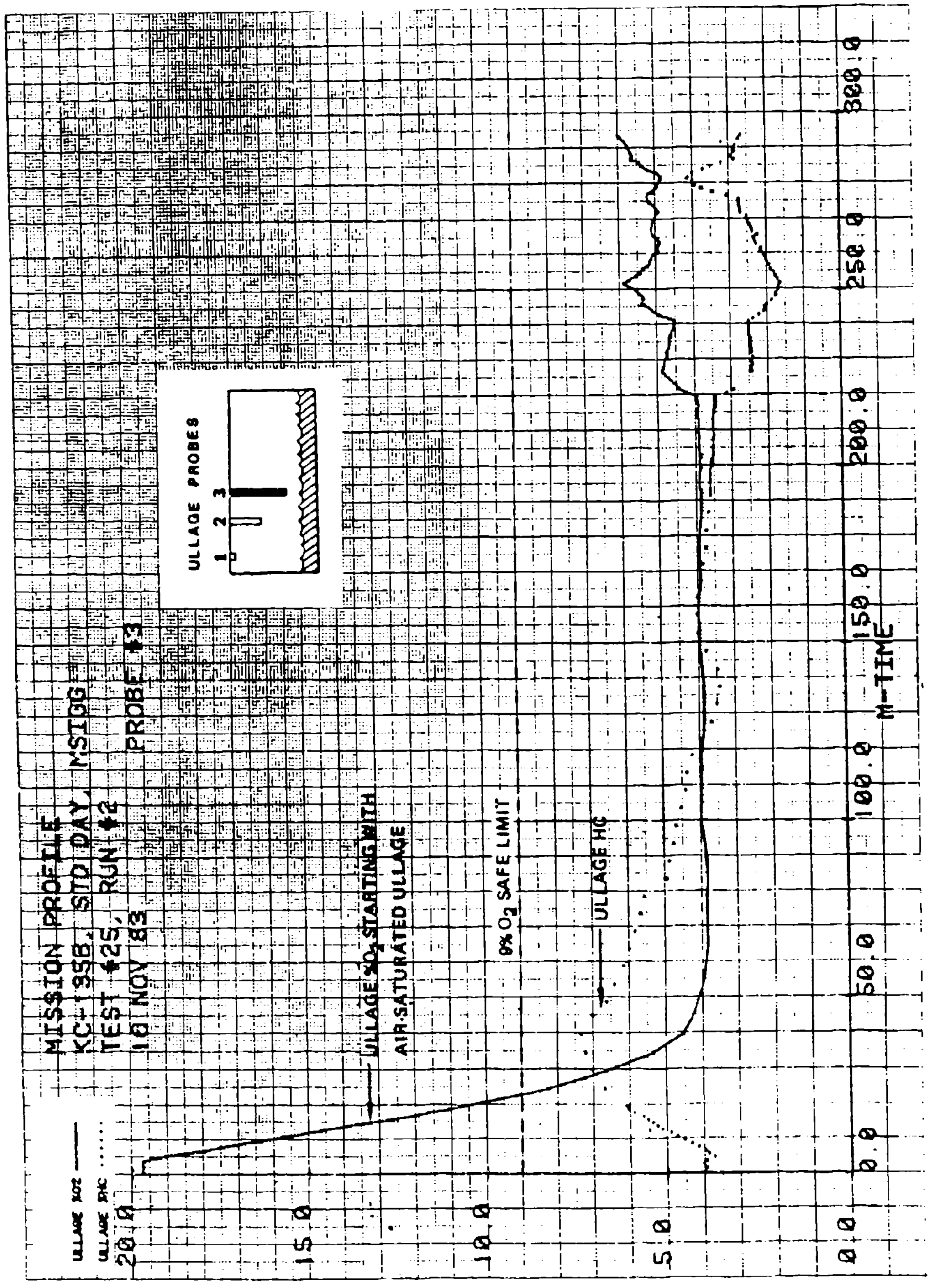
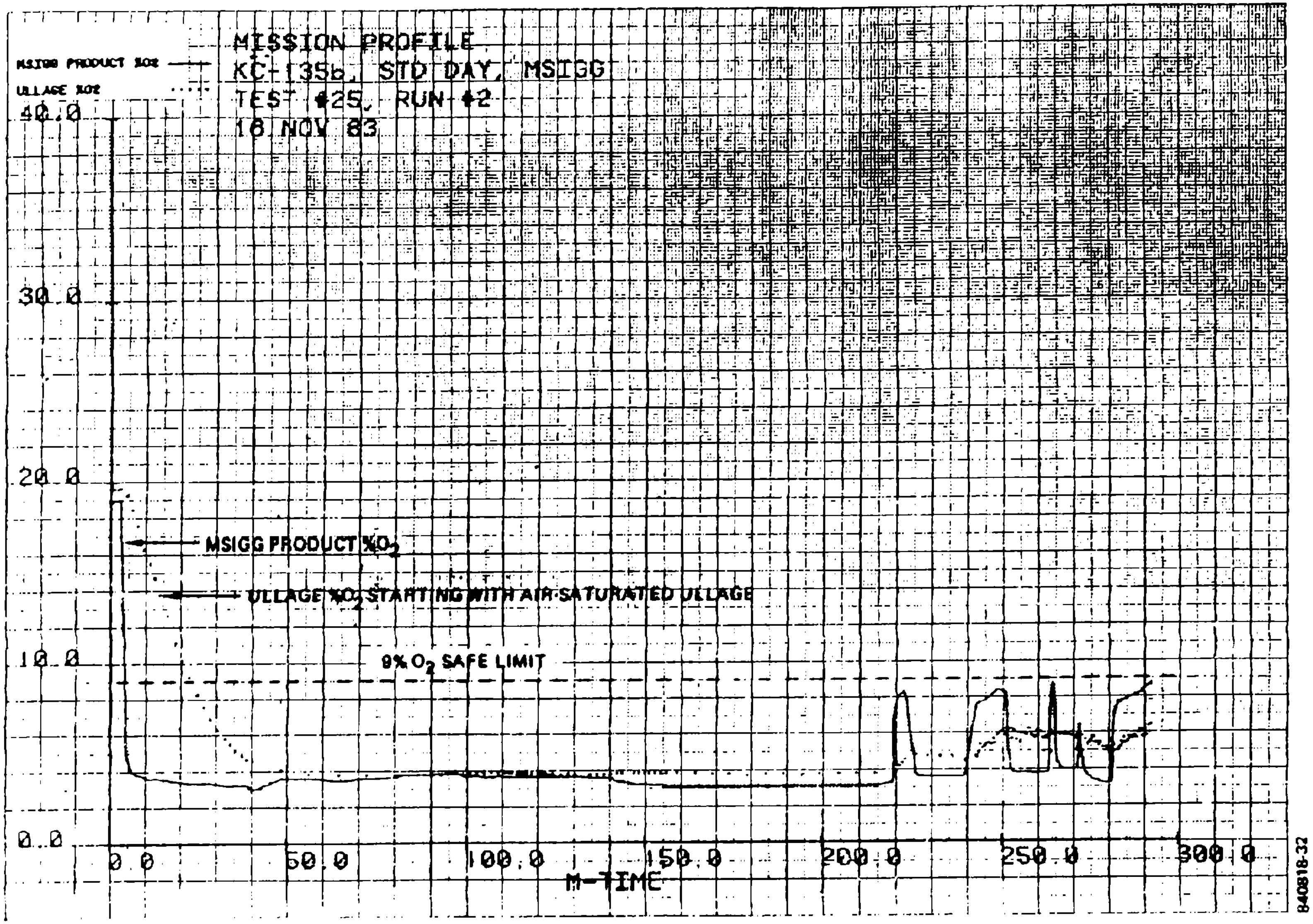


Figure H-8.



MSIGG PRODUCT %O2
ULLAGE %O2
MISSION PROFILE
KC-135b, STD DAY, MSIGG
TEST #25, RUN #2
16 NOV 83
40.0
30.0
20.0
10.0
0.0
MSIGG PRODUCT %O2
ULLAGE %O2 STARTING WITH AIR-SATURATED ULLAGE
9% O2 SAFE LIMIT
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
840818-32

Figure H-9.

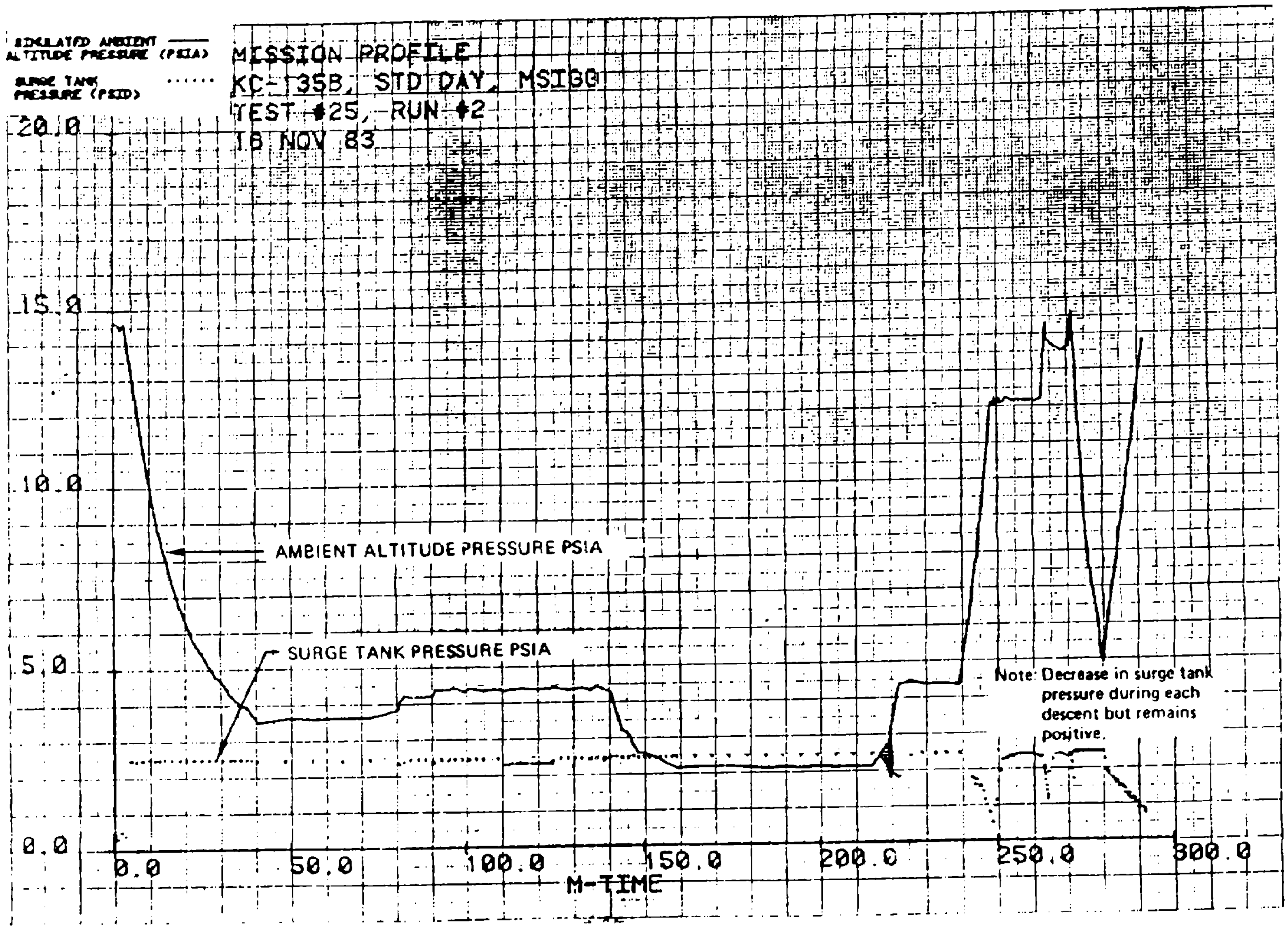

SIMULATED AMBIENT ALTITUDE PRESSURE (PSIA)
SURGE TANK PRESSURE (PSID)
MISSION PROFILE
KC-135B, STD DAY, MSIBO
TEST #25, RUN #2
18 NOV 83
20.0
15.0
10.0
5.0
0.0
AMBIENT ALTITUDE PRESSURE PSIA
SURGE TANK PRESSURE PSIA
Note: Decrease in surge tank pressure during each descent but remains positive.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
840818-33

Figure H-10.

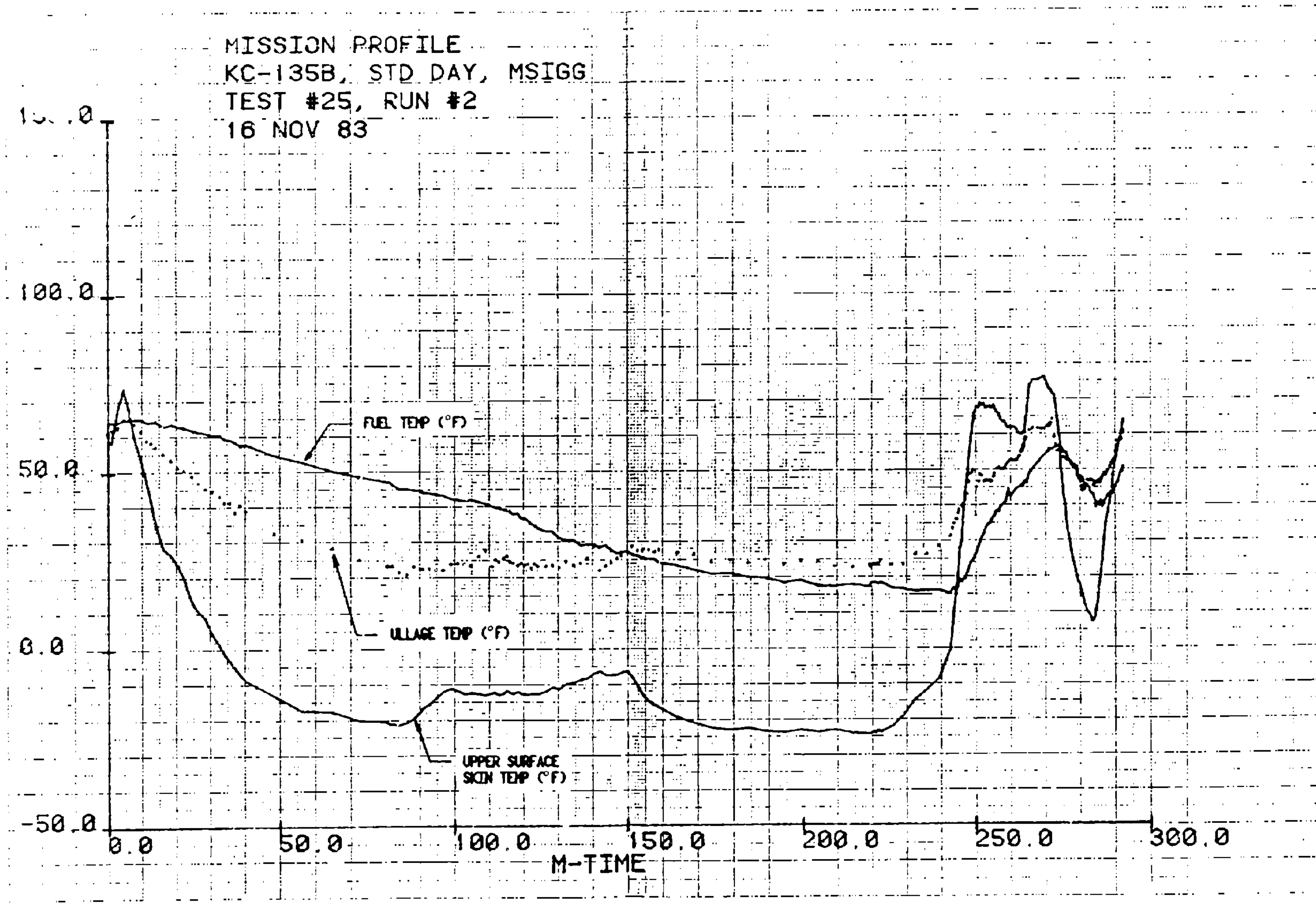

MISSION PROFILE
KC-135B, STD DAY, MSIGG
TEST #25, RUN #2
16 NOV 83
100.0
50.0
0.0
-50.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
FUEL TEMP (°F)
ULLAGE TEMP (°F)
UPPER SURFACE
SKIN TEMP (°F)

Figure H-11.

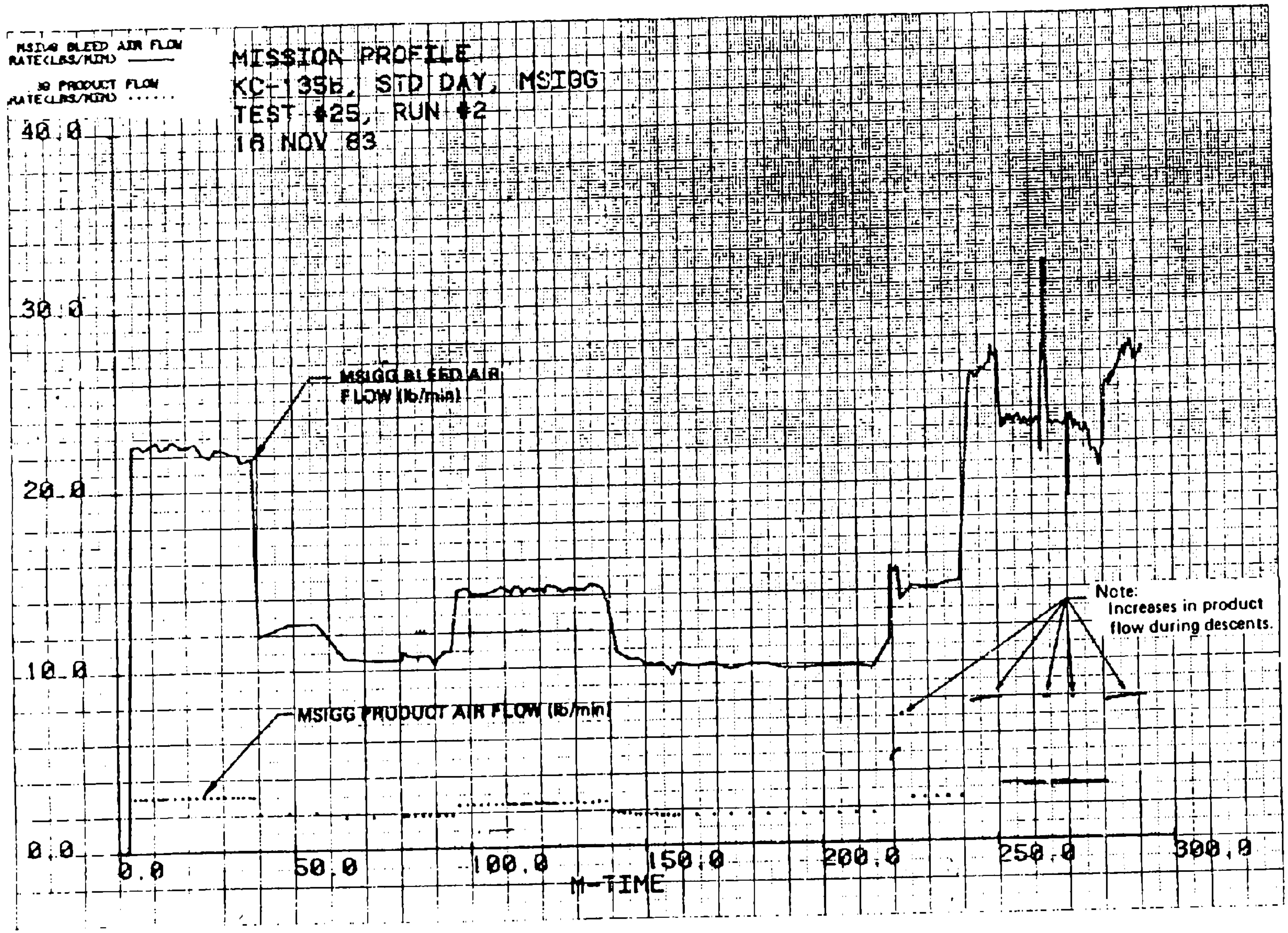

MSIGG BLEED AIR FLOW RATE(LBS/MIN)
PRODUCT FLOW RATE(LBS/MIN)
MISSION PROFILE
KC-135B, STD DAY, MSIGG
TEST #25, RUN #2
18 NOV 83
40.0
30.0
20.0
10.0
0.0
MSIGG BLEED AIR FLOW (lb/min)
MSIGG PRODUCT AIR FLOW (lb/min)
Note:
Increases in product flow during descents.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
840818-36

Figure H-12.

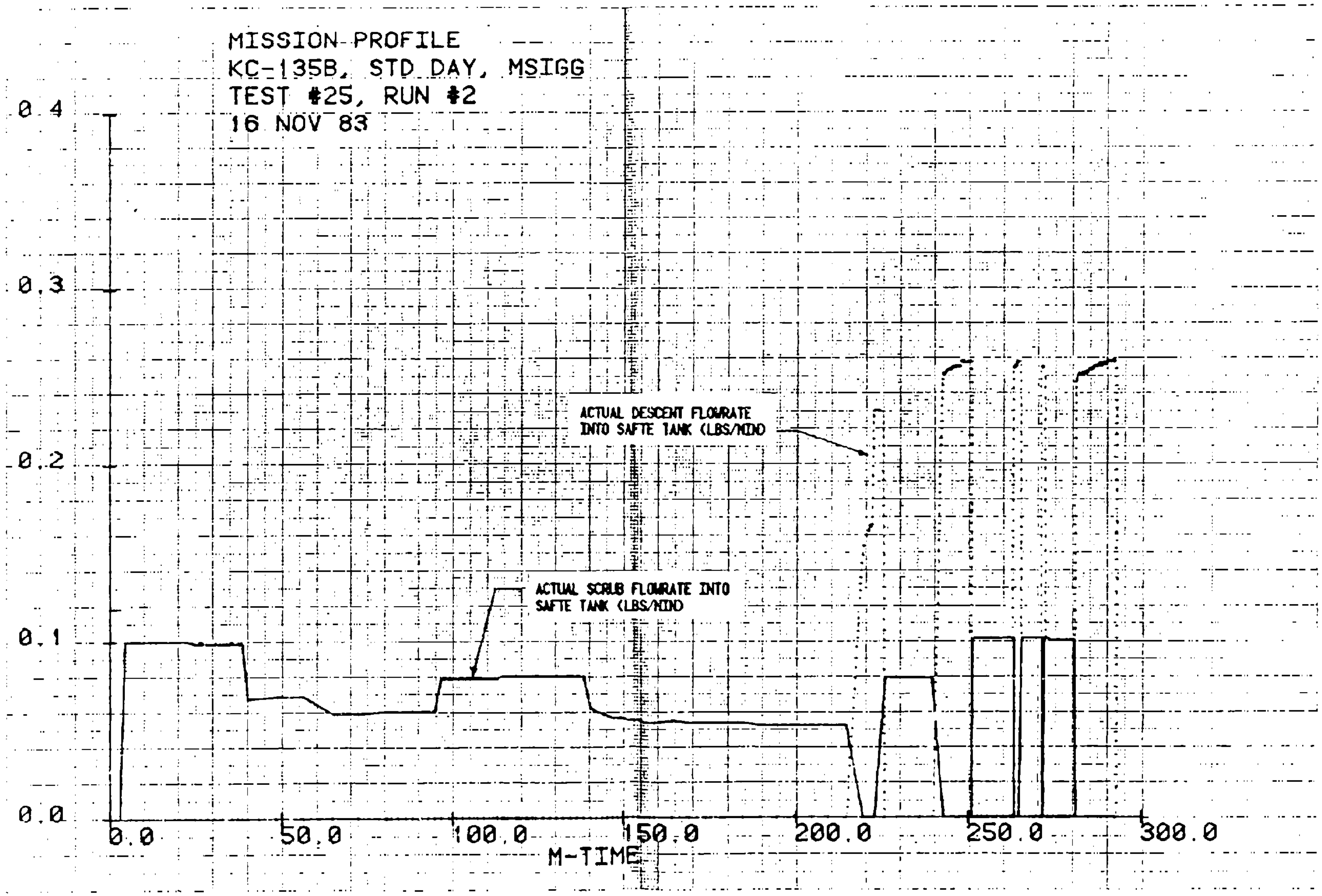
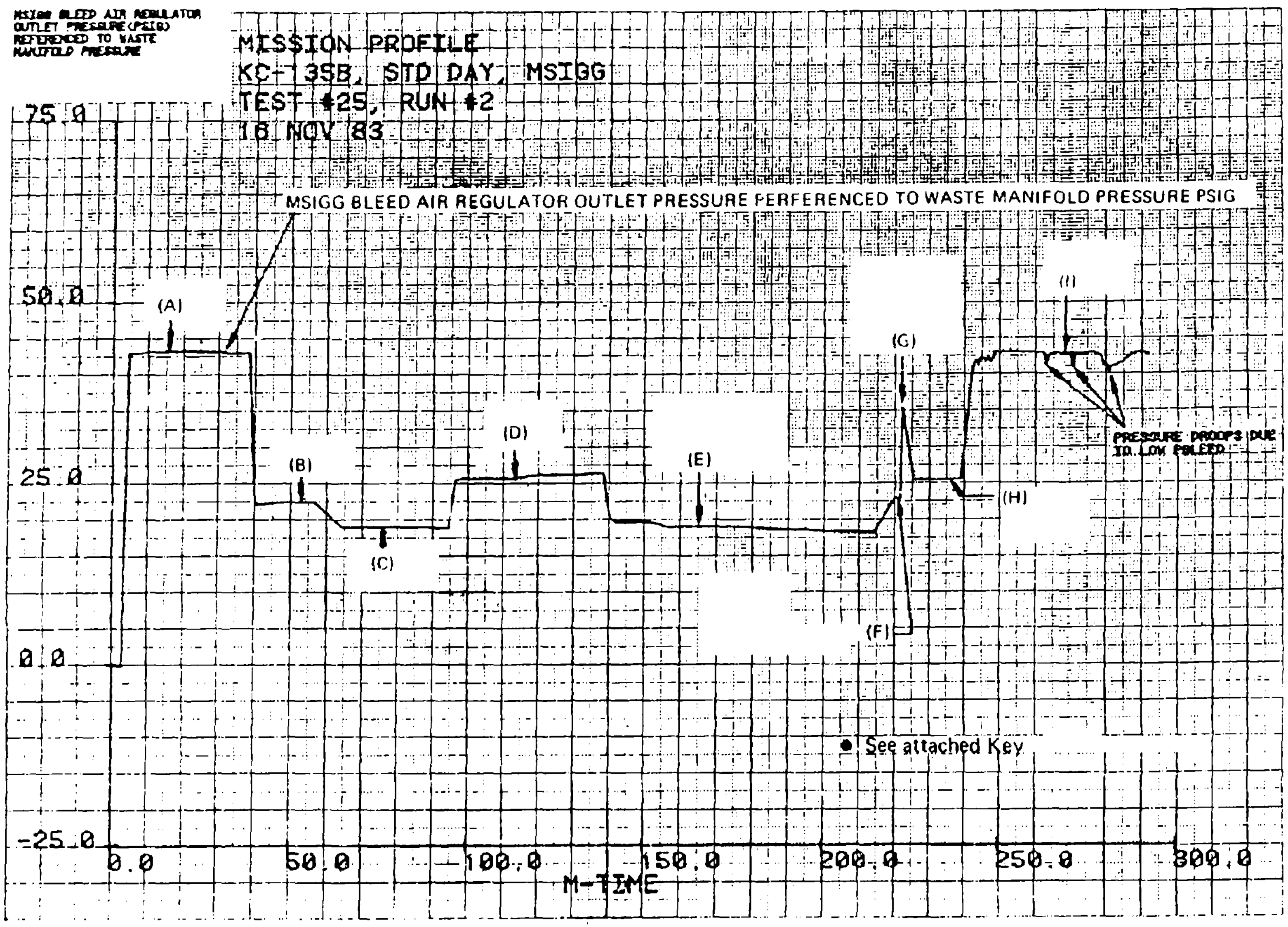

MISSION PROFILE
KC-135B, STD DAY, MSIGG
TEST #25, RUN #2
16 NOV 83
ACTUAL DESCENT FLOWRATE INTO SAFTE TANK (LBS/MIN)
ACTUAL SCRUB FLOWRATE INTO SAFTE TANK (LBS/MIN)
0.4
0.3
0.2
0.1
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME

Figure H-13.



840818-38

Figure H-14.

Key to Figure H-14

(A) 430 psig*
3 PPM
<30K ft
>54°F

(B) 23.0 psig*
3 PPM
>30K ft
>54°F

(C) 19.5 psig*
3 PPM
>30K ft
30-54°F

(D) 25.9 psig*
3 PPM
<30K ft
30-54°F

(E) 11.5 psig*
3 PPM
>30K ft
30-54°F
Pressure drops due to low P bleed

(F) 25.9 psig*
3 PPM
<30K ft
30-54°F
Cannot reach 25.9 psig due to low P bleed

(H) 25.9 psig*
3 PPM
<30 K ft
30-54°F

(I) 42.0 psig*
3 & 8 PPM
<30K ft
<54°F

*Denotes regulator setting as per schedule.

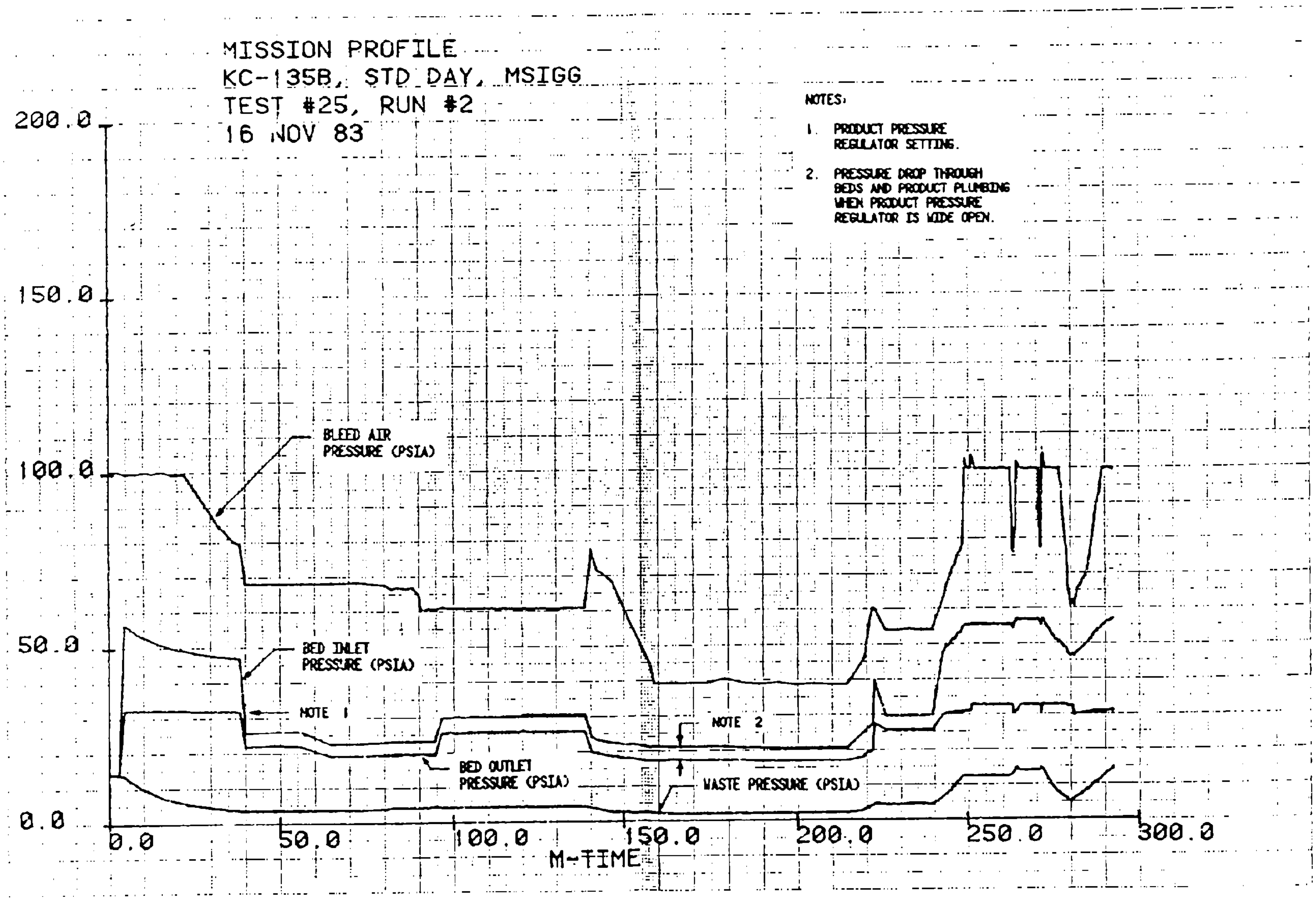

MISSION PROFILE
KC-135B, STD DAY, MSIGG
TEST #25, RUN #2
16 NOV 83
NOTES:
1. PRODUCT PRESSURE REGULATOR SETTING.
2. PRESSURE DROP THROUGH BEDS AND PRODUCT PLUMBING WHEN PRODUCT PRESSURE REGULATOR IS WIDE OPEN.
BLEED AIR PRESSURE (PSIA)
BED INLET PRESSURE (PSIA)
NOTE 1
NOTE 2
BED OUTLET PRESSURE (PSIA)
WASTE PRESSURE (PSIA)
200.0
150.0
100.0
50.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME

Figure H-15.

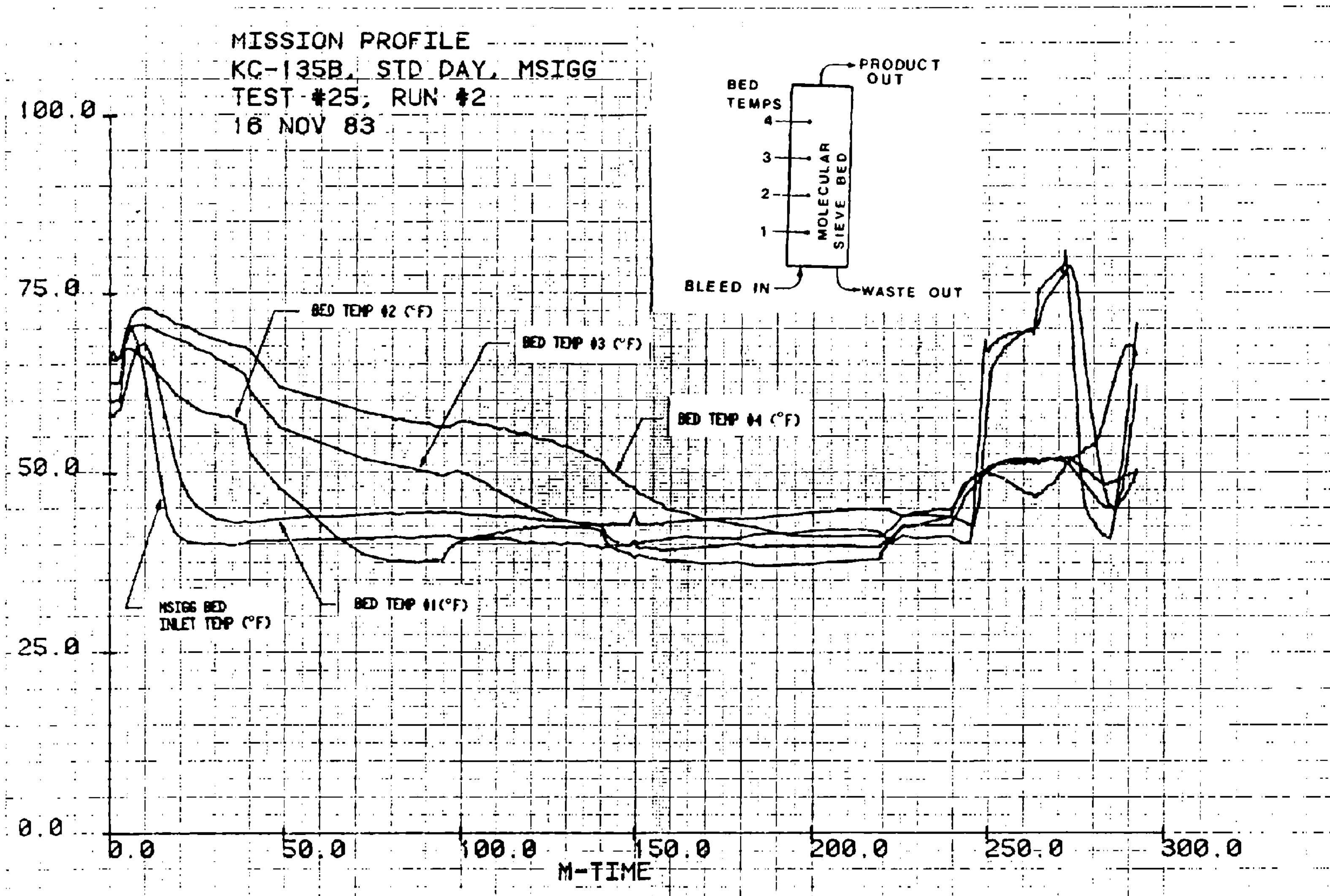
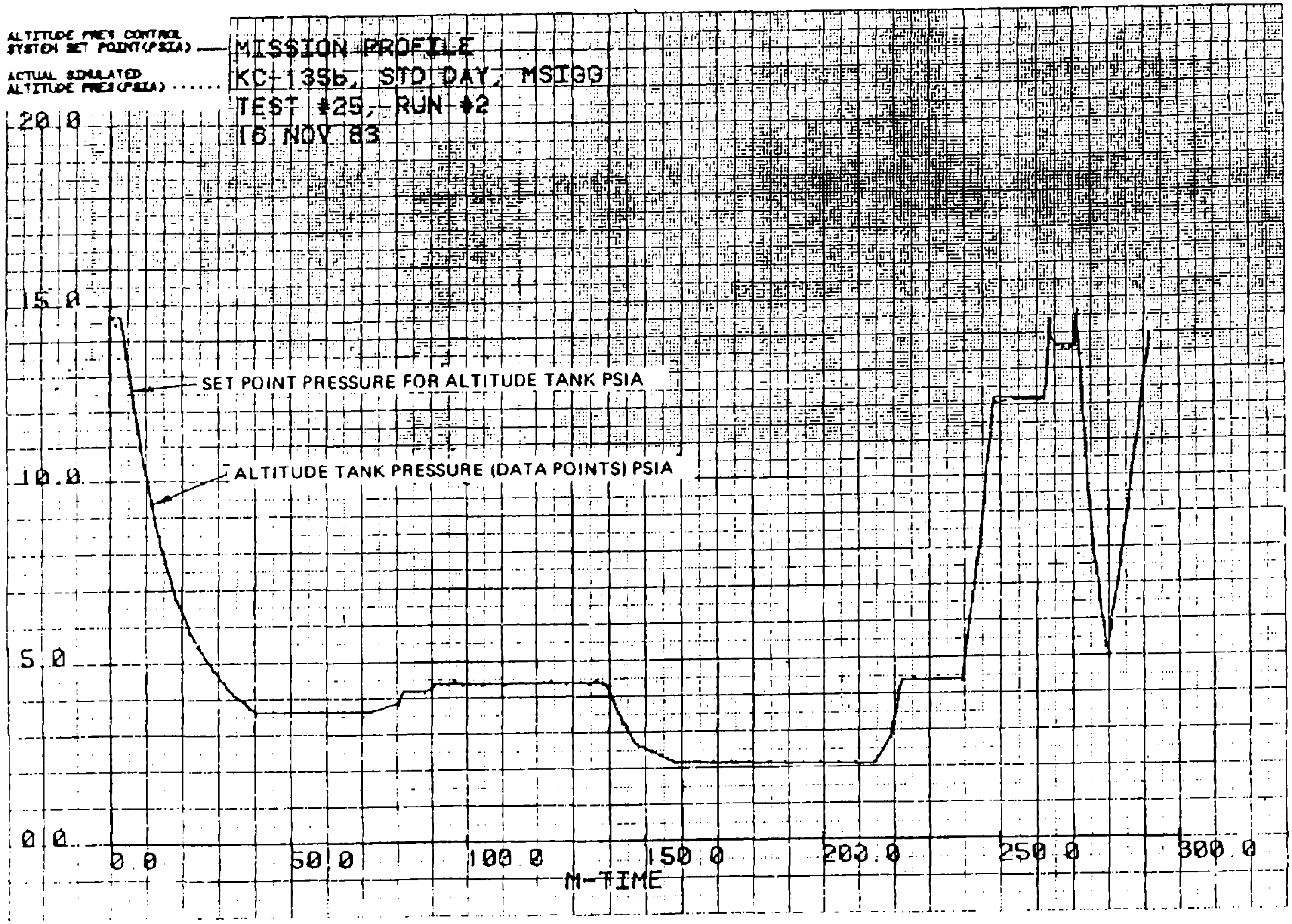
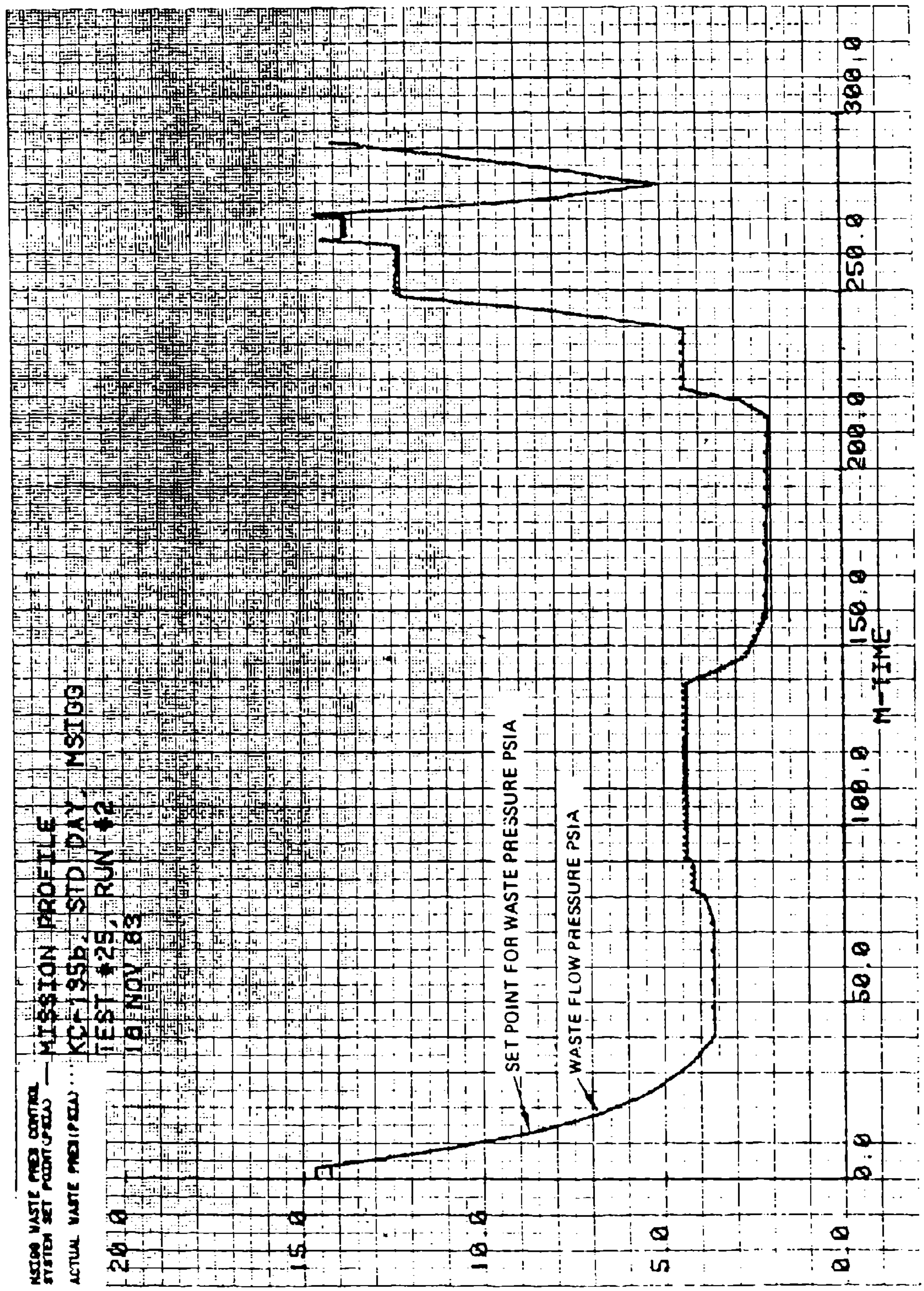

MISSION PROFILE
KC-135B, STD DAY, MSIGG
TEST #25, RUN #2
16 NOV 83
BED TEMPS
4
3
2
1
MOLECULAR SIEVE BED
PRODUCT OUT
BLEED IN
WASTE OUT
BED TEMP #2 (°F)
BED TEMP #3 (°F)
BED TEMP #4 (°F)
MSIGG BED INLET TEMP (°F)
BED TEMP #1(°F)
100.0
75.0
50.0
25.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME

Figure H-16.



ALTITUDE PRES CONTROL SYSTEM SET POINT (PSIA)
ACTUAL SIMULATED ALTITUDE PRES (PSIA)
MISSION PROFILE
KC-135b, STD DAY, MSTGG
TEST #25, RUN #2
16 NOV 83
SET POINT PRESSURE FOR ALTITUDE TANK PSIA
ALTITUDE TANK PRESSURE (DATA POINTS) PSIA
20.0
15.0
10.0
5.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
840818-44

Figure H-17.



WASTE PRES CONTROL
SYSTEM SET POINT (PSIA)
ACTUAL WASTE PRES (PSIA)
MISSION PROFILE
KC-135b, STD DAY, MSTDG
TEST #25, RUN #2
10 NOV 83
SET POINT FOR WASTE PRESSURE PSIA
WASTE FLOW PRESSURE PSIA
20.0
15.0
10.0
5.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME

Figure H.18

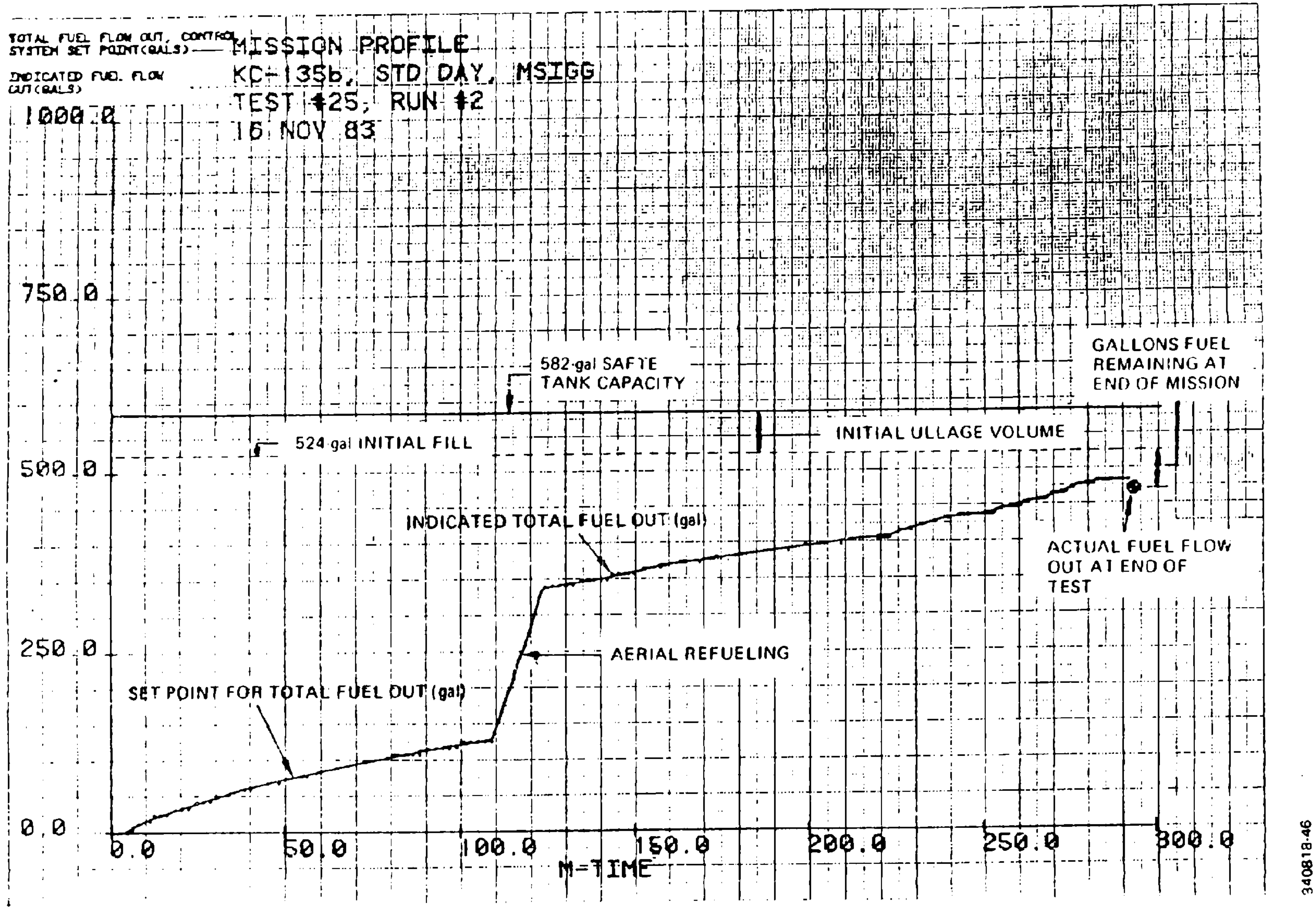
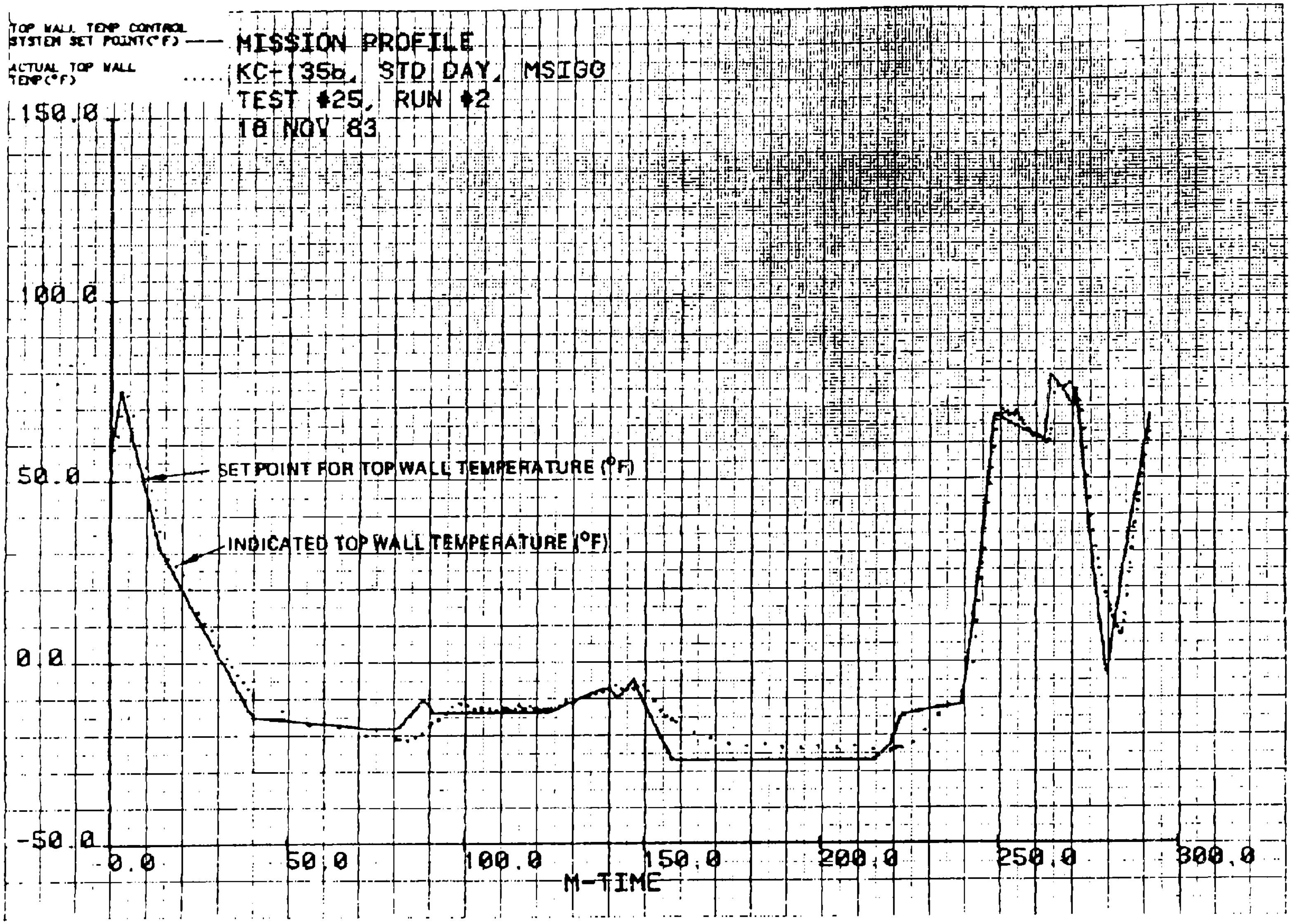

TOTAL FUEL FLOW OUT, CONTROL SYSTEM SET POINT (GALS)
INDICATED FUEL FLOW OUT (GALS)
MISSION PROFILE
KC-135b, STD DAY, MSIGG
TEST #25, RUN #2
16 NOV 83
1000.0
750.0
500.0
250.0
0.0
582-gal SAFTE TANK CAPACITY
524 gal INITIAL FILL
INITIAL ULLAGE VOLUME
GALLONS FUEL REMAINING AT END OF MISSION
INDICATED TOTAL FUEL OUT (gal)
ACTUAL FUEL FLOW OUT AT END OF TEST
AERIAL REFUELING
SET POINT FOR TOTAL FUEL OUT (gal)
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
340818-46

Figure H-19.



TOP WALL TEMP CONTROL SYSTEM SET POINT(°F)
ACTUAL TOP WALL TEMP(°F)
MISSION PROFILE
KC-135b, STD DAY, MSIGO
TEST #25, RUN #2
18 NOV 83
150.0
100.0
50.0
0.0
-50.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
SET POINT FOR TOP WALL TEMPERATURE (°F)
INDICATED TOP WALL TEMPERATURE (°F)
840818-47

Figure H-20.

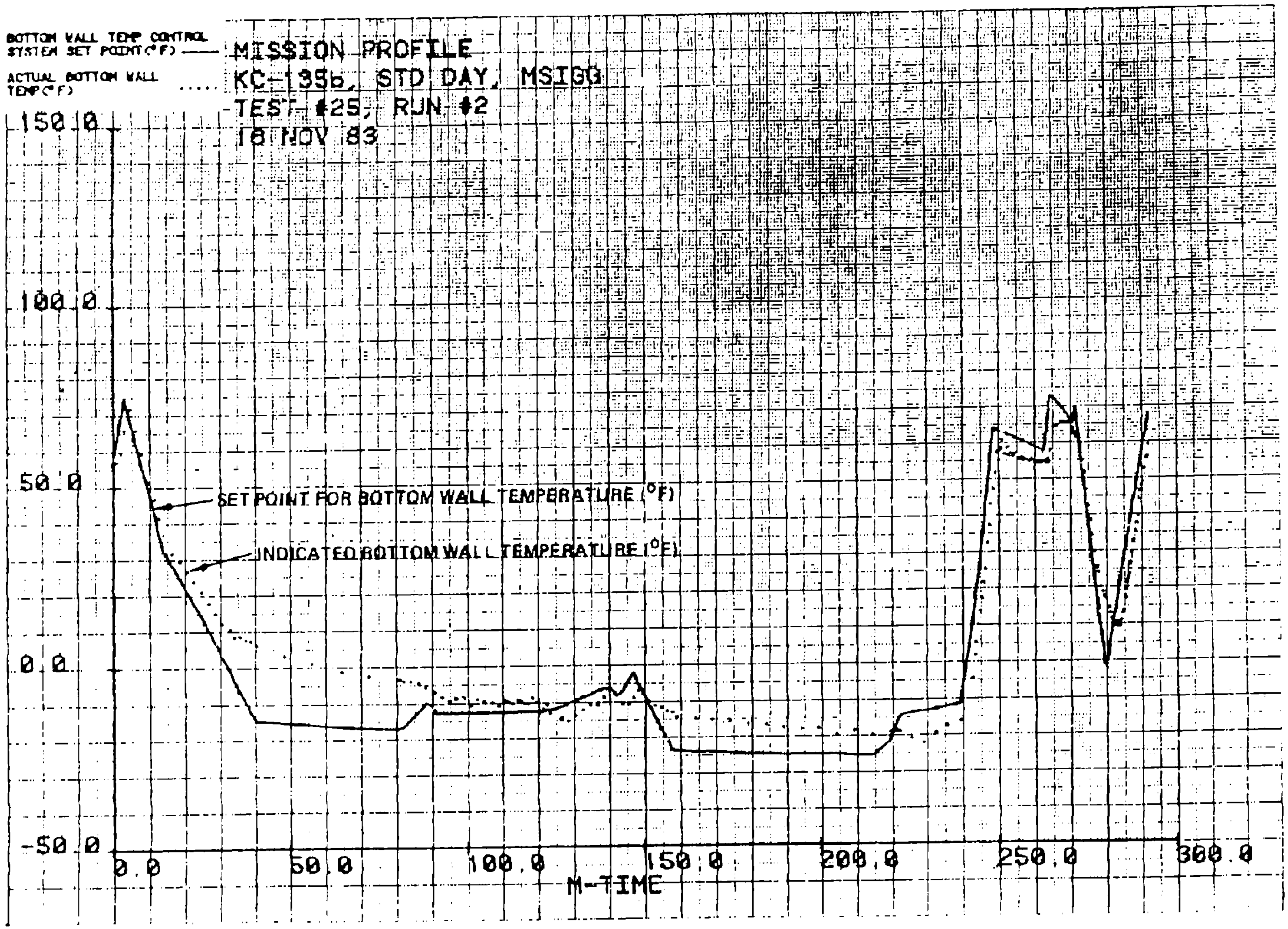

BOTTOM WALL TEMP CONTROL SYSTEM SET POINT (°F)
ACTUAL BOTTOM WALL TEMP (°F)
MISSION PROFILE
KC-135b, STD DAY, MSIGG
TEST #25, RUN #2
18 NOV 83
SET POINT FOR BOTTOM WALL TEMPERATURE (°F)
INDICATED BOTTOM WALL TEMPERATURE (°F)
150.0
100.0
50.0
0.0
-50.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
840818-48

Figure H-21.

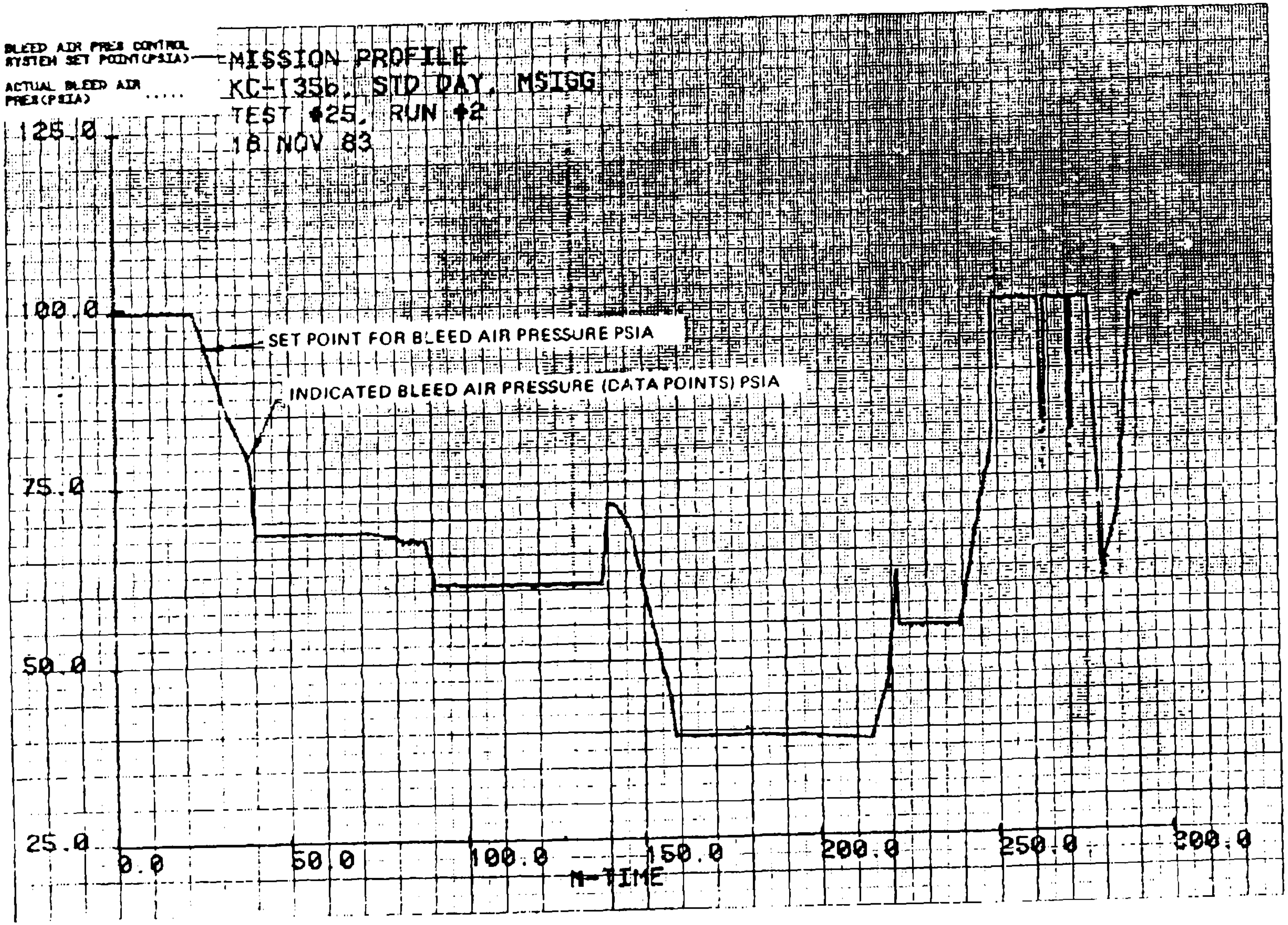
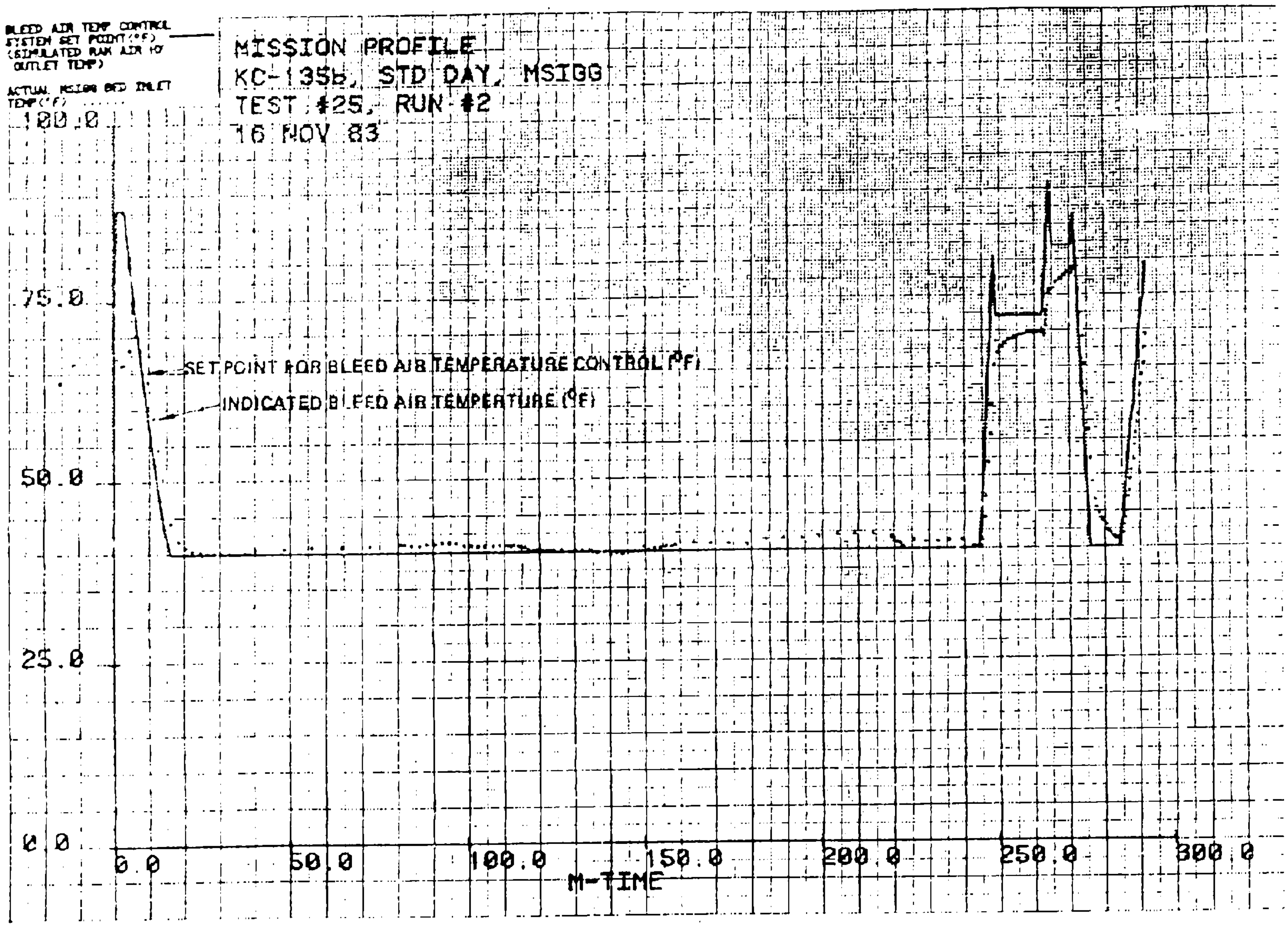

BLEED AIR PRES CONTROL SYSTEM SET POINT(PSIA)
ACTUAL BLEED AIR PRES(PSIA)
MISSION PROFILE
KC-135b, STD DAY, MSIGG
TEST #25, RUN #2
18 NOV 83
SET POINT FOR BLEED AIR PRESSURE PSIA
INDICATED BLEED AIR PRESSURE (DATA POINTS) PSIA
125.0
100.0
75.0
50.0
25.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
840818-49

Figure H-22.



840318-50

Figure H-23.

APPENDIX I

PMIGG Detailed Mission Simulation Data Plots

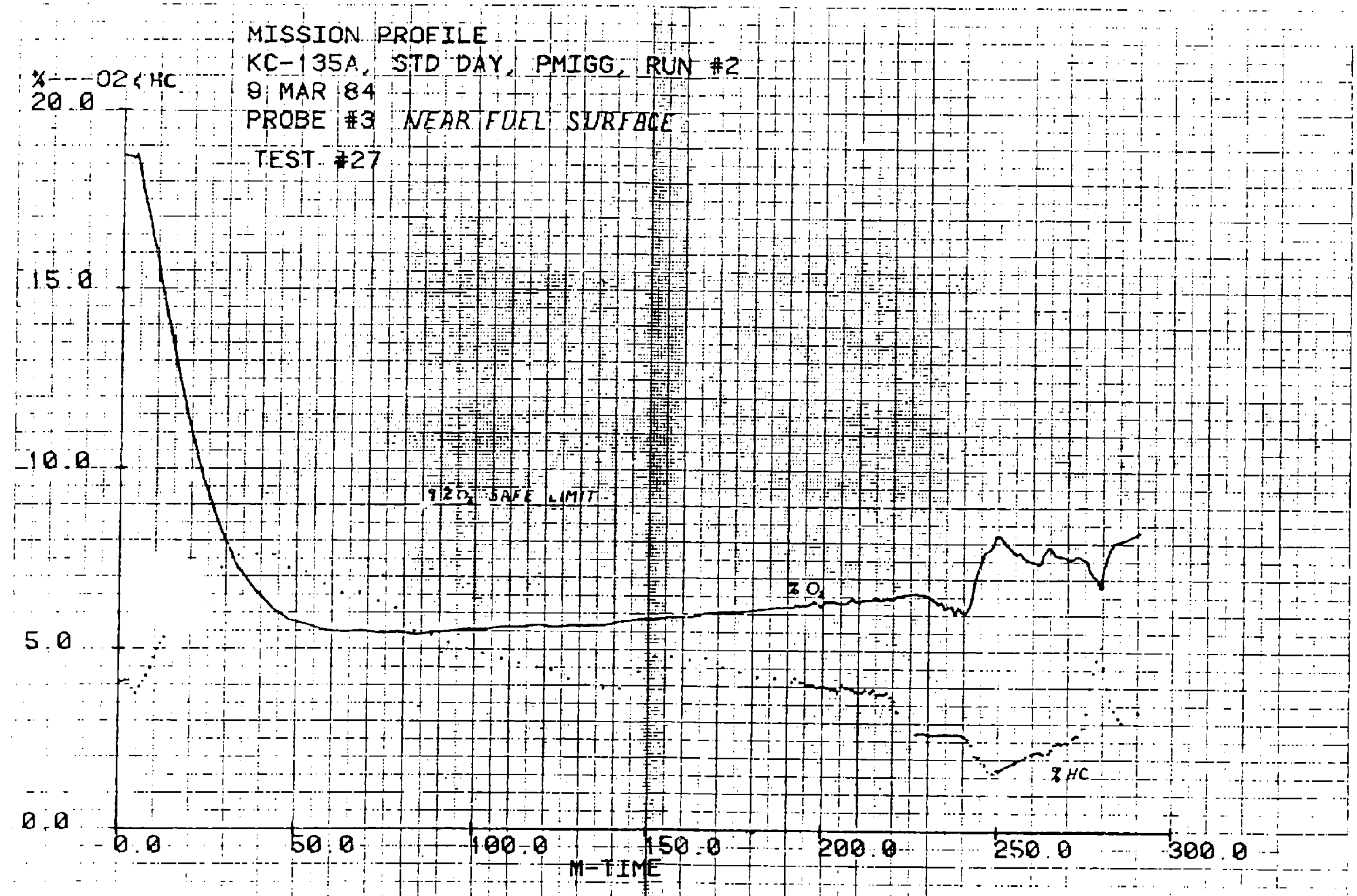


Figure I-1.

47 1510

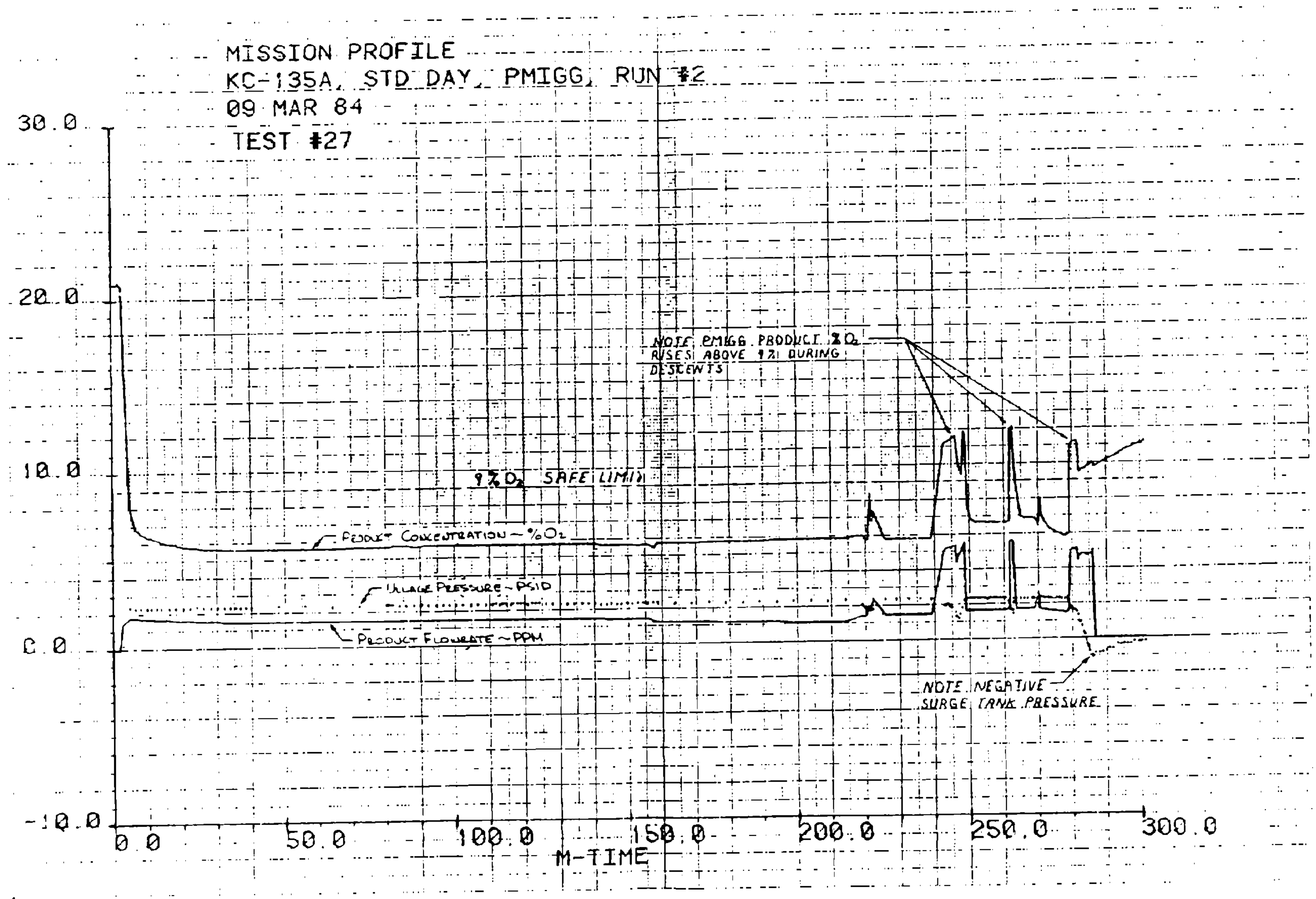

MISSION PROFILE
KC-135A, STD DAY, PMIGG, RUN #2
09 MAR 84
TEST #27
30.0
20.0
10.0
0.0
-10.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
9% O_2 SAFE LIMIT
PRODUCT CONCENTRATION ~ % O_2
ULLAGE PRESSURE ~ PSID
PRODUCT FLOWRATE ~ PPM
NOTE PMIGG PRODUCT % O_2 RISES ABOVE 9% DURING DESCENTS
NOTE NEGATIVE SURGE TANK PRESSURE

Figure I-2.

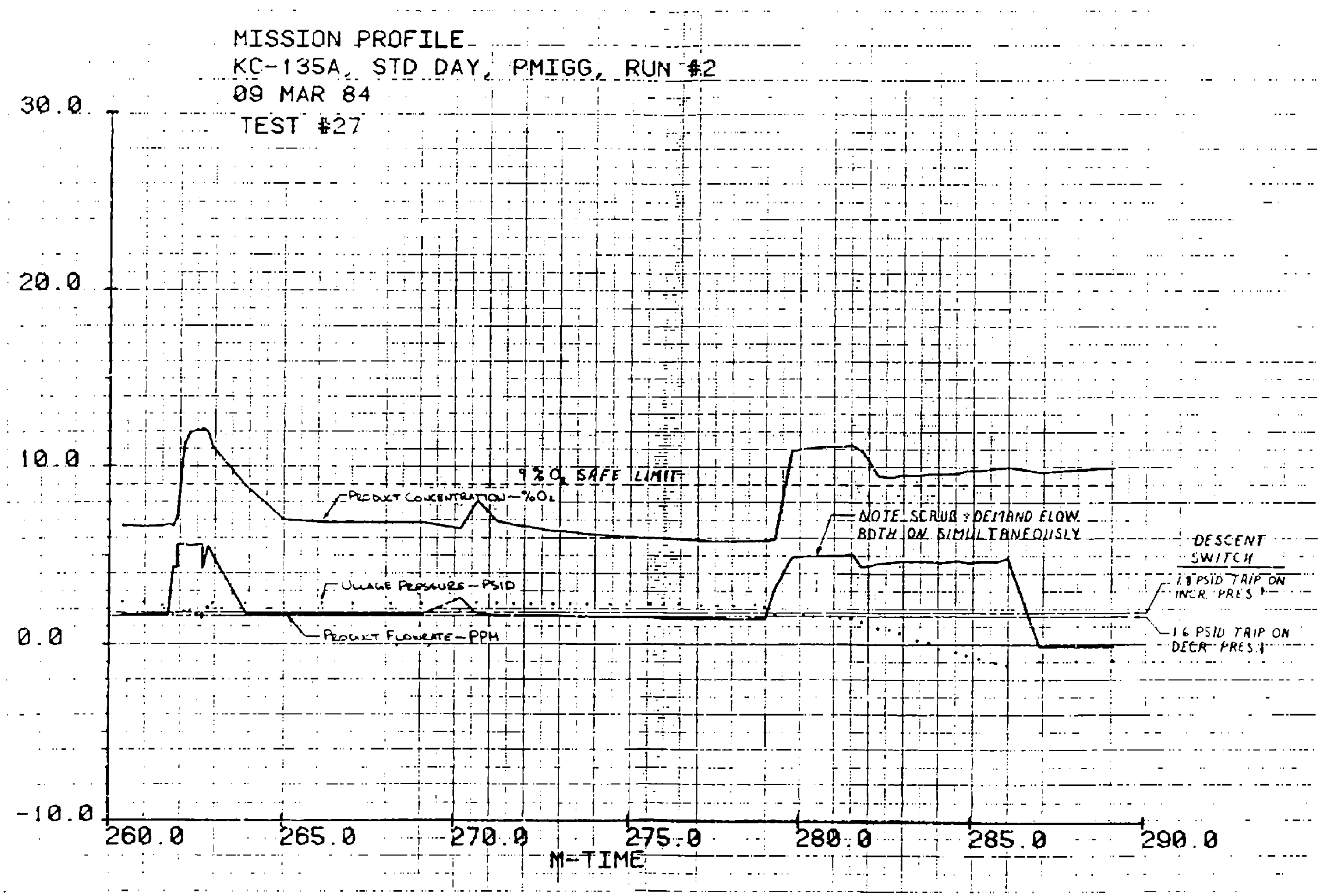

MISSION PROFILE
KC-135A, STD DAY, PMIGG, RUN #2
09 MAR 84
TEST #27
30.0
20.0
10.0
0.0
-10.0
260.0
265.0
270.0
275.0
280.0
285.0
290.0
M-TIME
9% O2 SAFE LIMIT
PRODUCT CONCENTRATION – %O2
ULLAGE PRESSURE – PSID
PRODUCT FLOWRATE – PPH
NOTE SCRUB & DEMAND FLOW
BOTH ON SIMULTANEOUSLY
DESCENT SWITCH
1.8 PSID TRIP ON INCR PRES
1.6 PSID TRIP ON DECR PRES

Figure I-3.

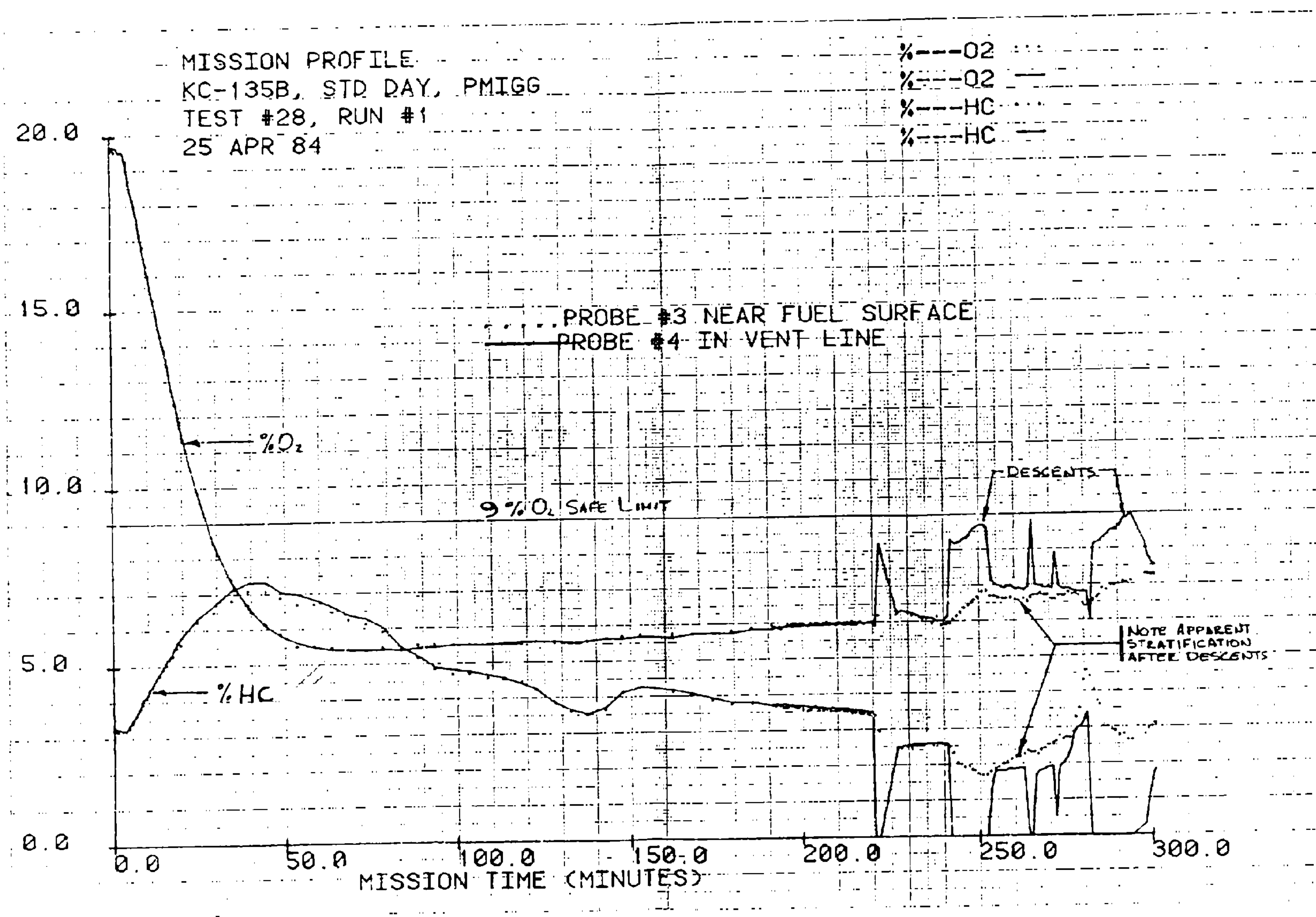

MISSION PROFILE
KC-135B, STD DAY, PMIGG
TEST #28, RUN #1
25 APR 84
%---O2
%---O2
%---HC
%---HC
PROBE #3 NEAR FUEL SURFACE
PROBE #4 IN VENT LINE
%O2
9% O2 SAFE LIMIT
%HC
DESCENTS
NOTE APPARENT STRATIFICATION AFTER DESCENTS
20.0
15.0
10.0
5.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
MISSION TIME (MINUTES)

Figure I-4.

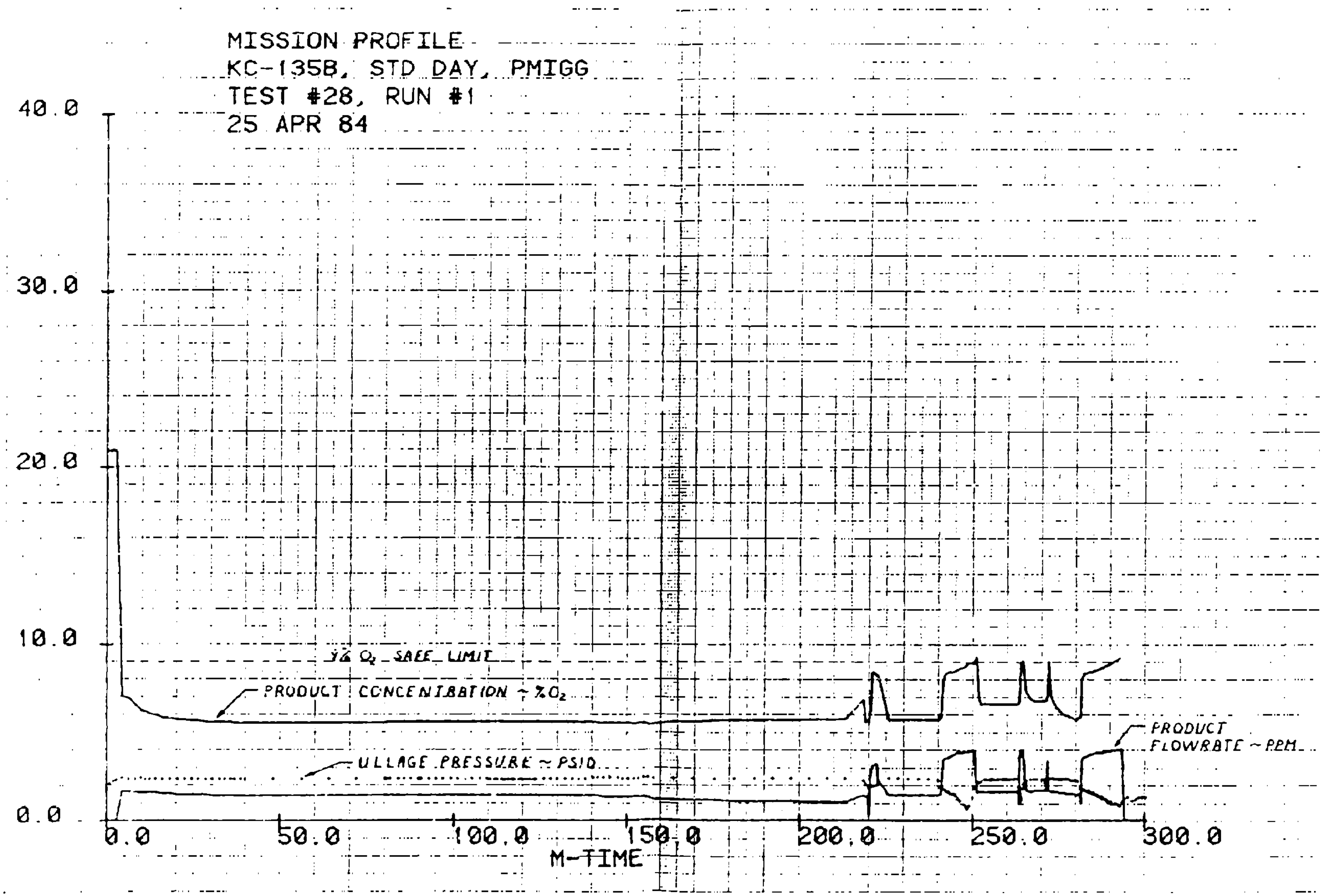

MISSION PROFILE
KC-135B, STD DAY, PMIGG
TEST #28, RUN #1
25 APR 84
40.0
30.0
20.0
10.0
0.0
9% O_2 SAFE LIMIT
PRODUCT CONCENTRATION ~ % O_2
ULLAGE PRESSURE ~ PSID
PRODUCT FLOWRATE ~ PPM
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME

Figure I-5.

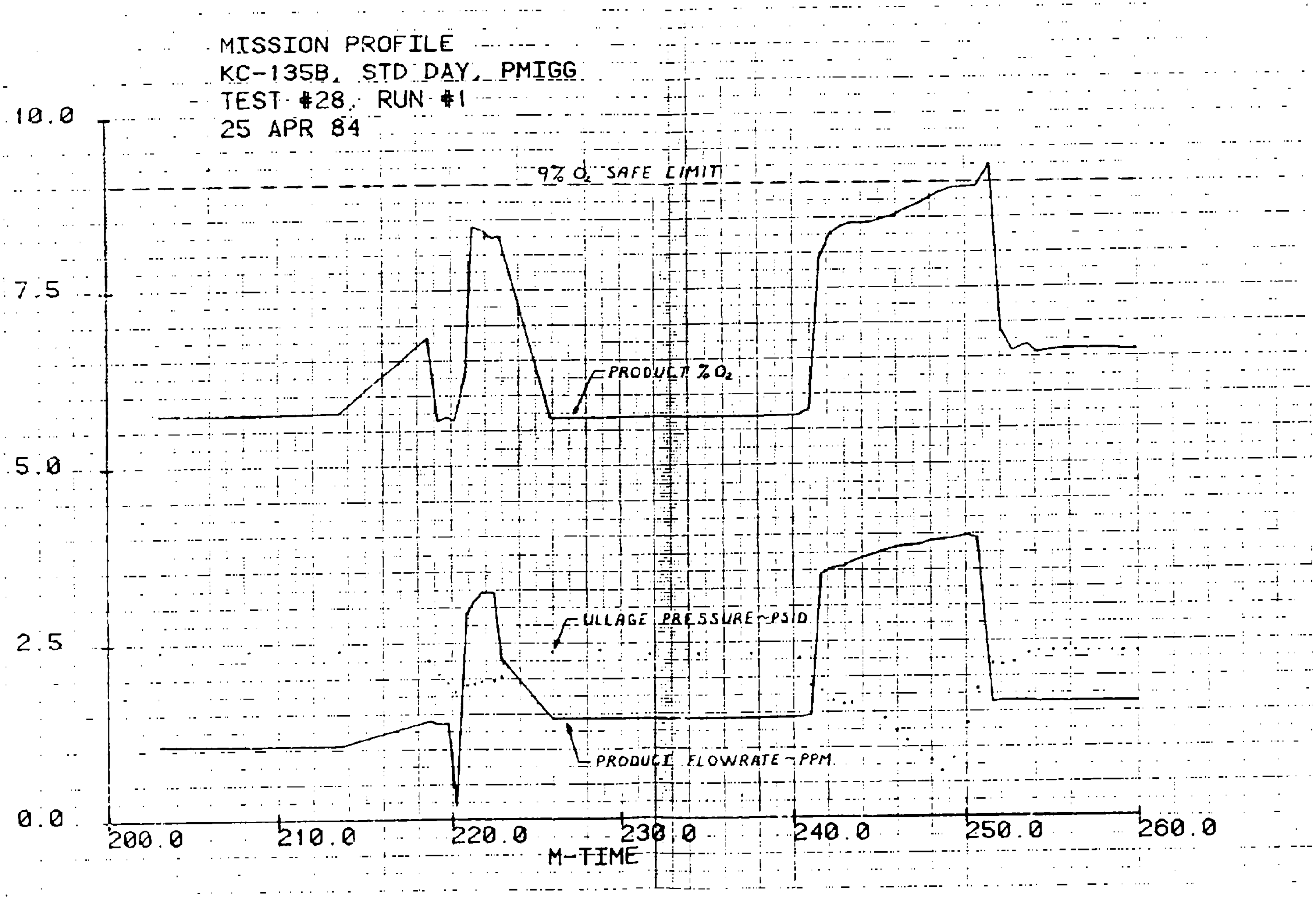

MISSION PROFILE
KC-135B, STD DAY, PMIGG
TEST #28, RUN #1
25 APR 84
9% O_2 SAFE LIMIT
PRODUCT % O_2
ULLAGE PRESSURE ~ PSID
PRODUCT FLOWRATE ~ PPM
10.0
7.5
5.0
2.5
0.0
200.0
210.0
220.0
230.0
240.0
250.0
260.0
M-TIME

Figure I-6.

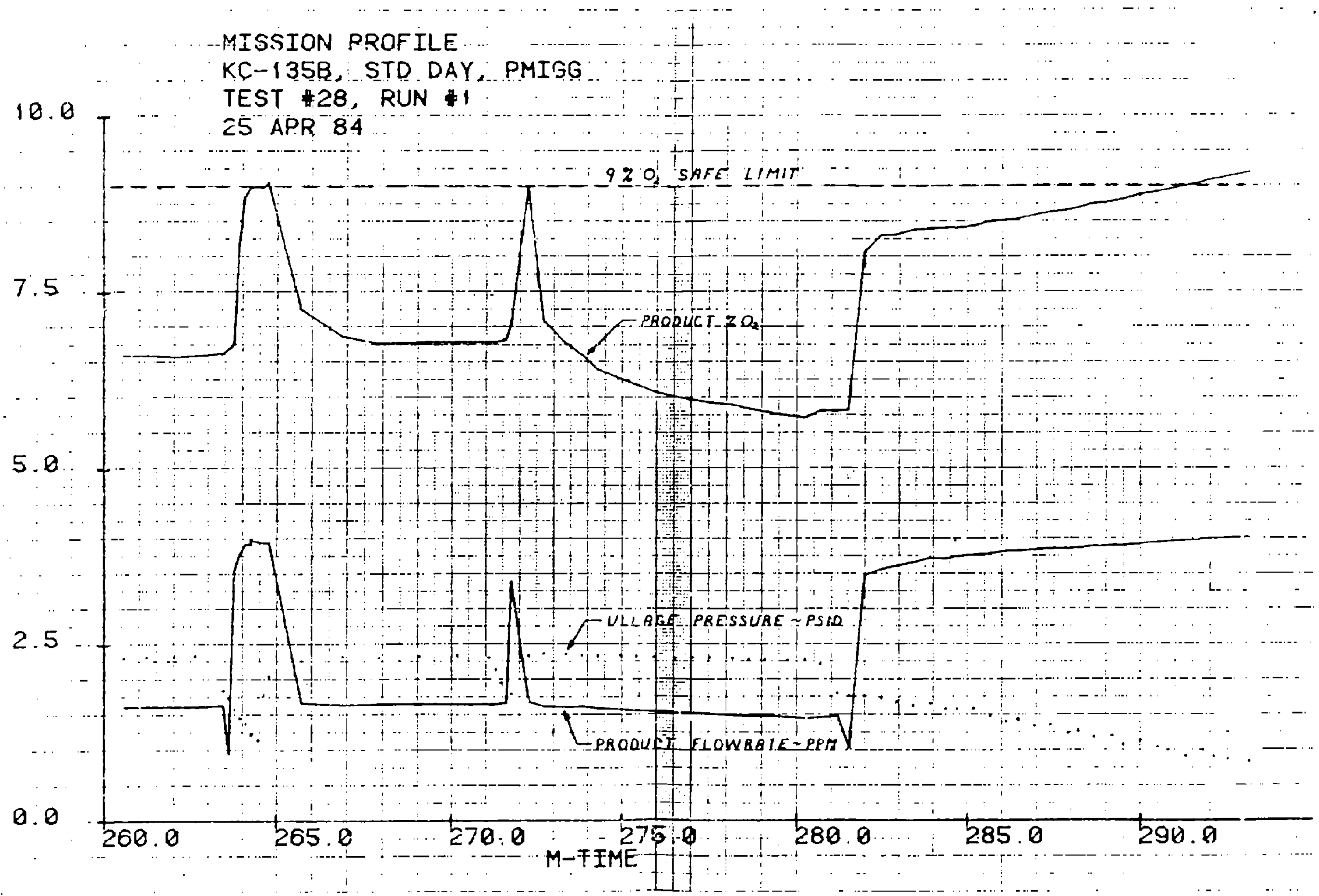

MISSION PROFILE
KC-135B, STD DAY, PMIGG
TEST #28, RUN #1
25 APR 84
9% O2 SAFE LIMIT
PRODUCT % O2
ULLAGE PRESSURE ~ PSID
PRODUCT FLOWRATE ~ PPM
10.0
7.5
5.0
2.5
0.0
260.0
265.0
270.0
275.0
280.0
285.0
290.0
M-TIME

Figure I-7.

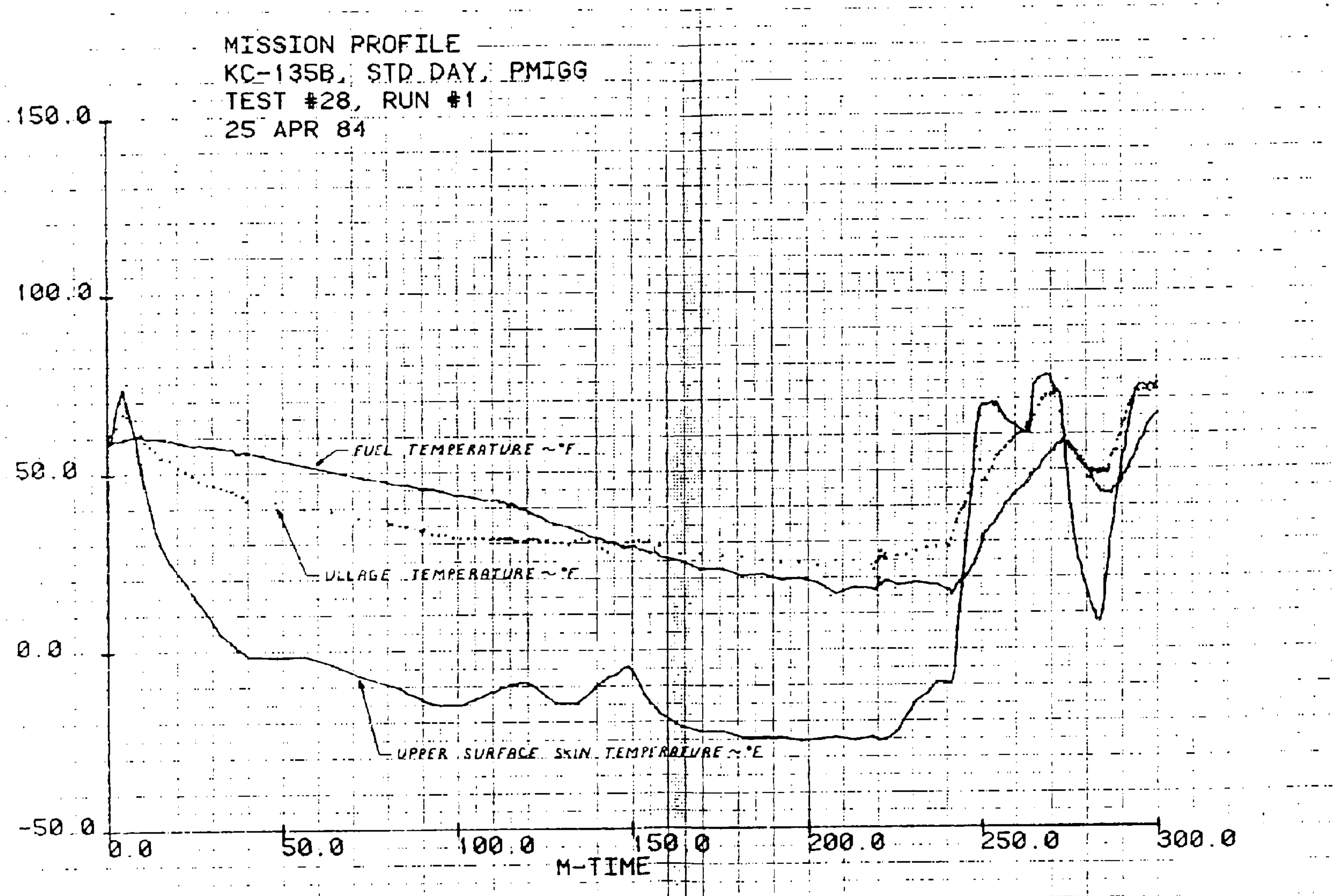

MISSION PROFILE
KC-135B, STD DAY, PMIGG
TEST #28, RUN #1
25 APR 84
FUEL TEMPERATURE ~°F
ULLAGE TEMPERATURE ~°F
UPPER SURFACE SKIN TEMPERATURE ~°F
150.0
100.0
50.0
0.0
-50.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME

Figure I-8.

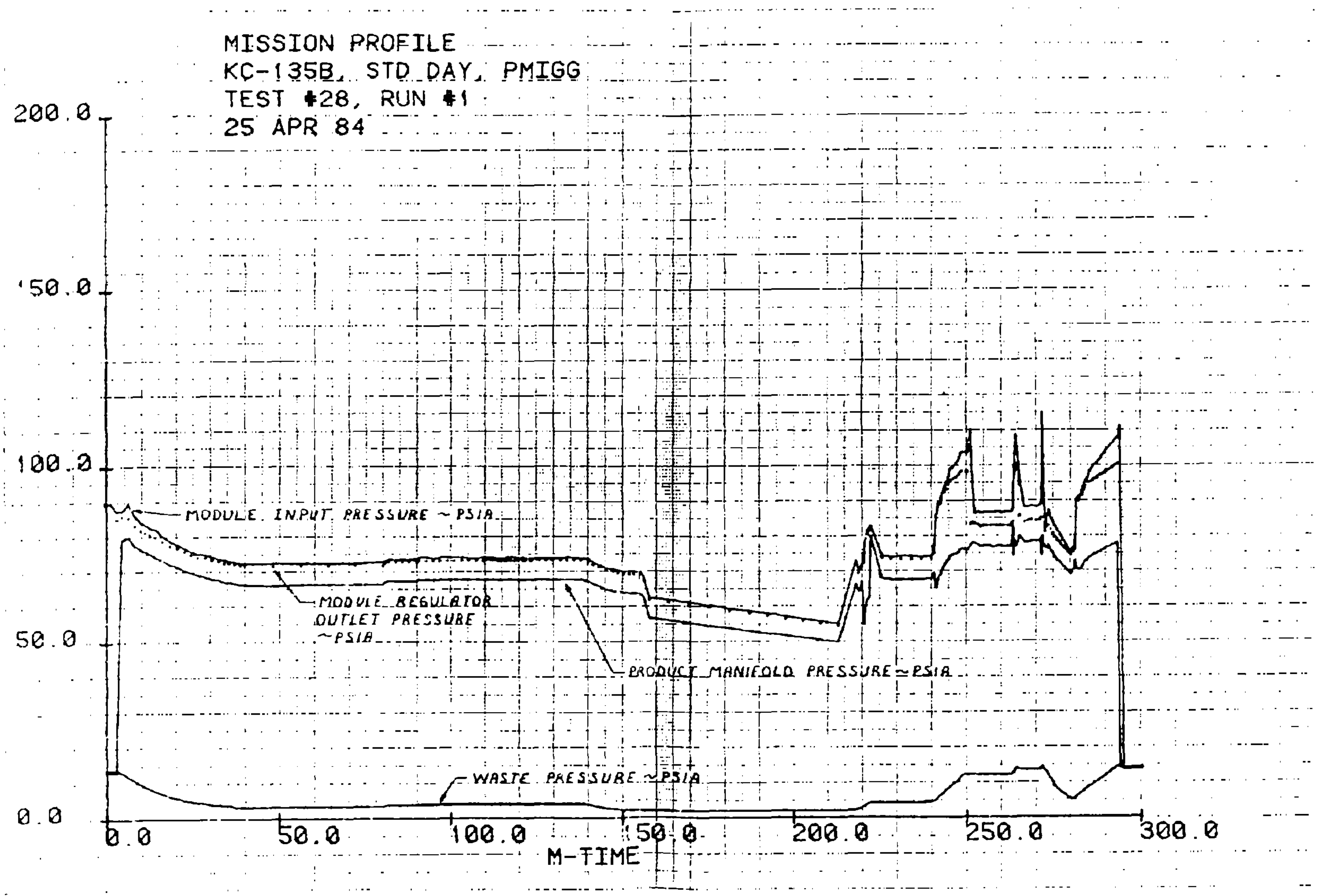

MISSION PROFILE
KC-135B, STD DAY, PMIGG
TEST #28, RUN #1
25 APR 84
200.0
150.0
100.0
50.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
MODULE INPUT PRESSURE ~ PSIA
MODULE REGULATOR OUTLET PRESSURE ~PSIA
PRODUCT MANIFOLD PRESSURE ~ PSIA
WASTE PRESSURE ~ PSIA

Figure I-9

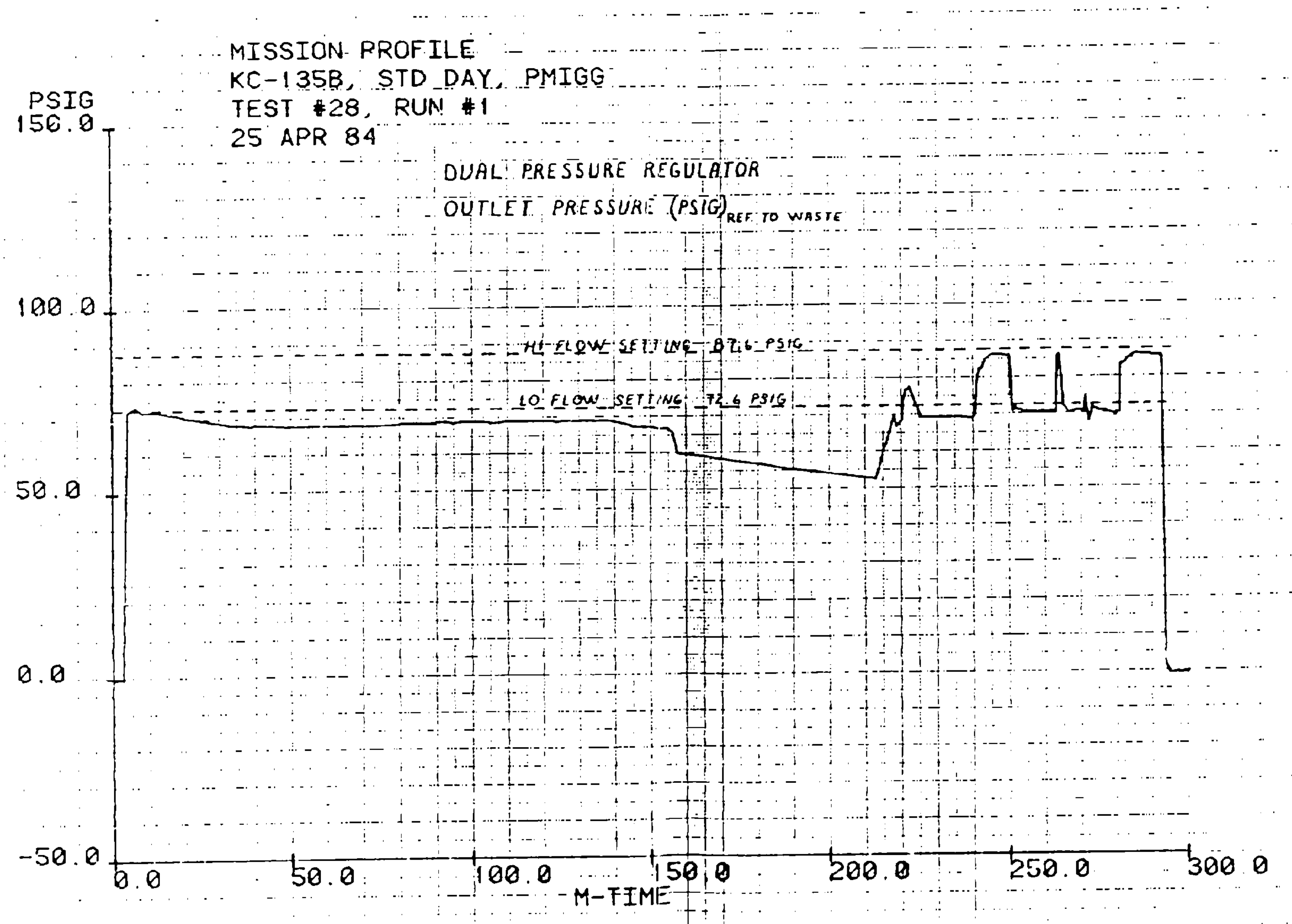

MISSION PROFILE
KC-135B, STD DAY, PMIGG
TEST #28, RUN #1
25 APR 84
DUAL PRESSURE REGULATOR
OUTLET PRESSURE (PSIG) REF TO WASTE
HI FLOW SETTING 87.6 PSIG
LO FLOW SETTING 72.6 PSIG
PSIG
150.0
100.0
50.0
0.0
-50.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME

Figure I-10.

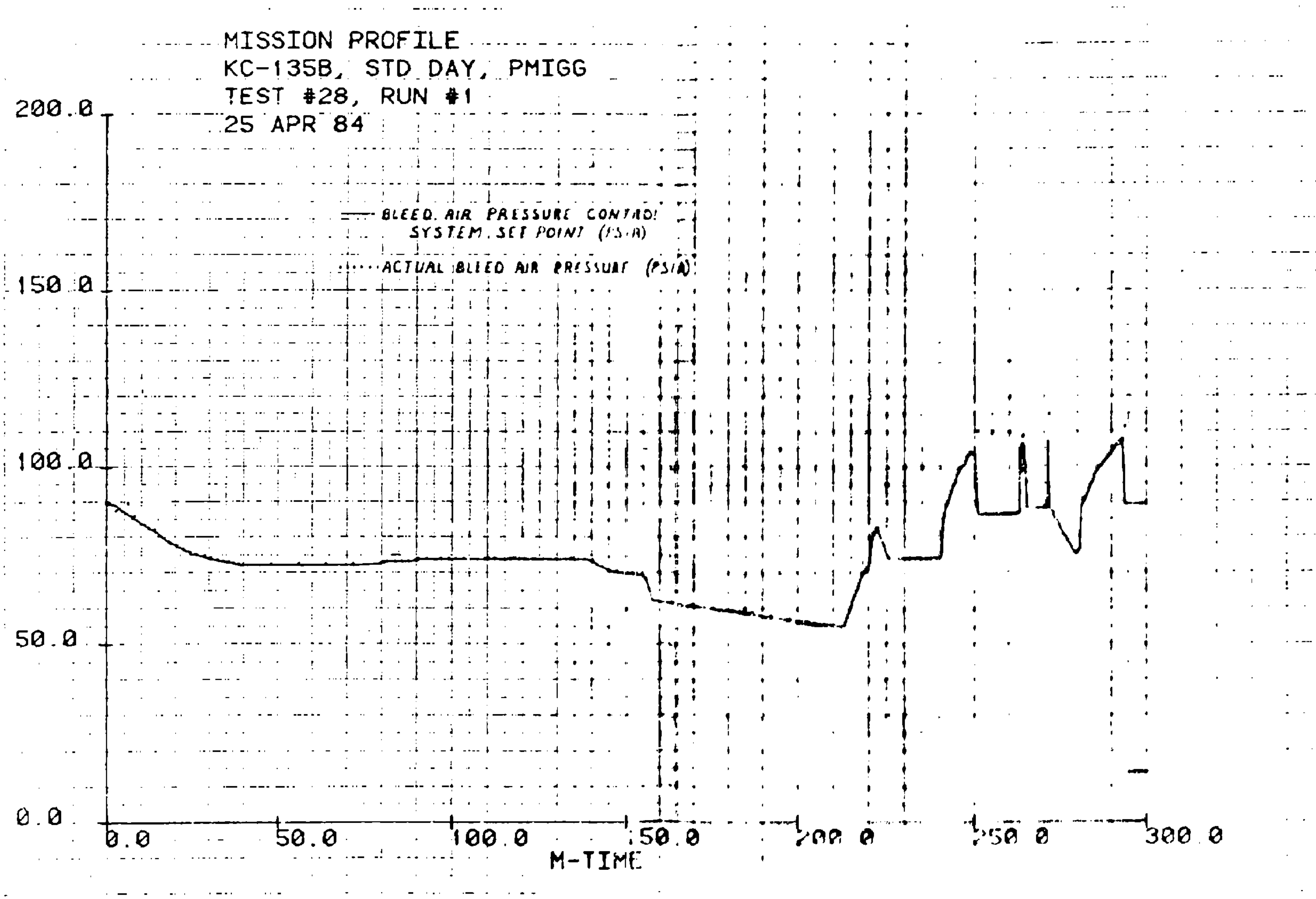
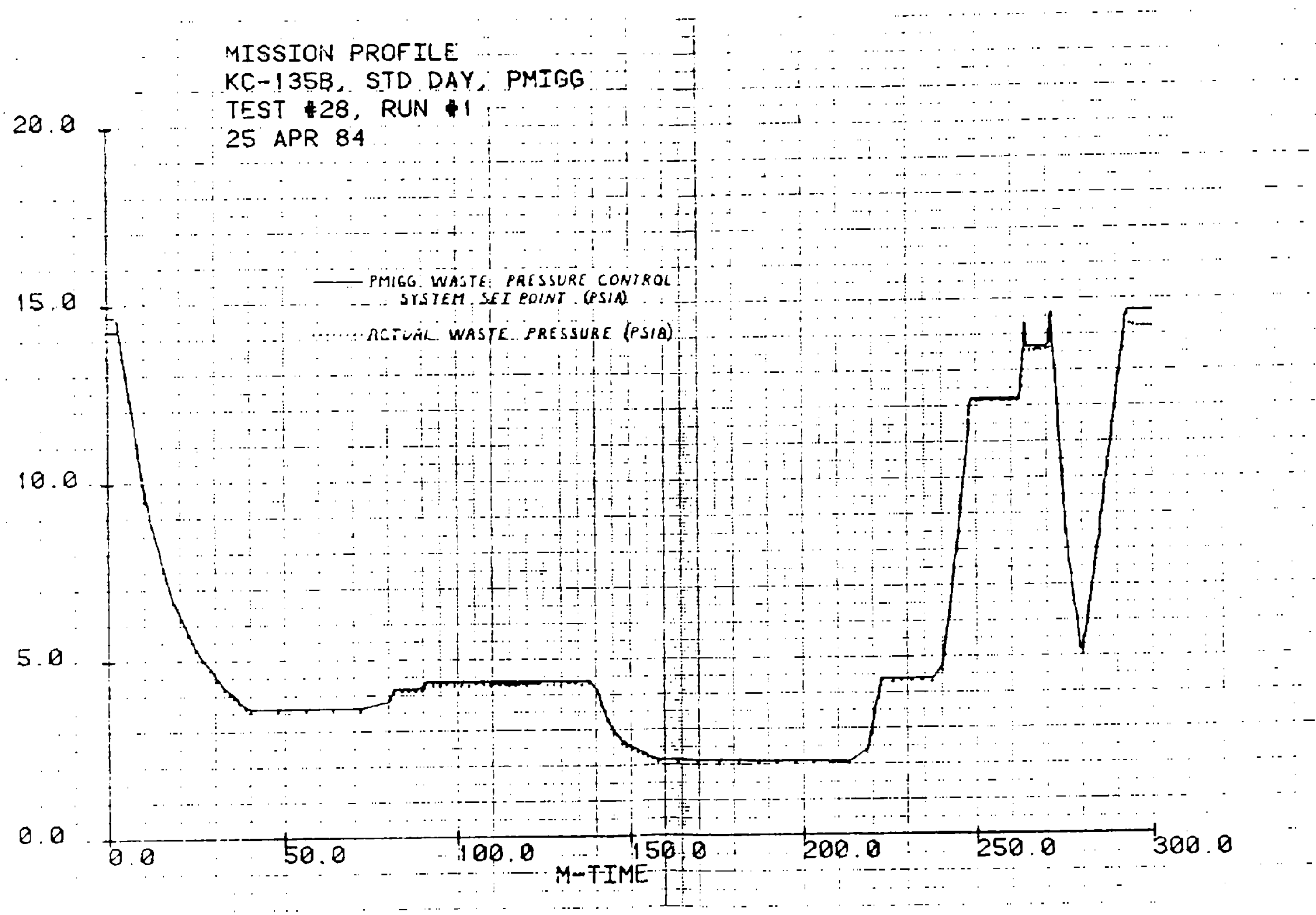

MISSION PROFILE
KC-135B, STD DAY, PMIGG
TEST #28, RUN #1
25 APR 84
BLEED AIR PRESSURE CONTROL SYSTEM SET POINT (PSIA)
ACTUAL BLEED AIR PRESSURE (PSIA)
200.0
150.0
100.0
50.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME

Figure I 11



MISSION PROFILE
KC-135B, STD DAY, PMIGG
TEST #28, RUN #1
25 APR 84
PMIGG WASTE PRESSURE CONTROL SYSTEM SET POINT (PSIA)
ACTUAL WASTE PRESSURE (PSIA)
20.0
15.0
10.0
5.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME

Figure I-12.

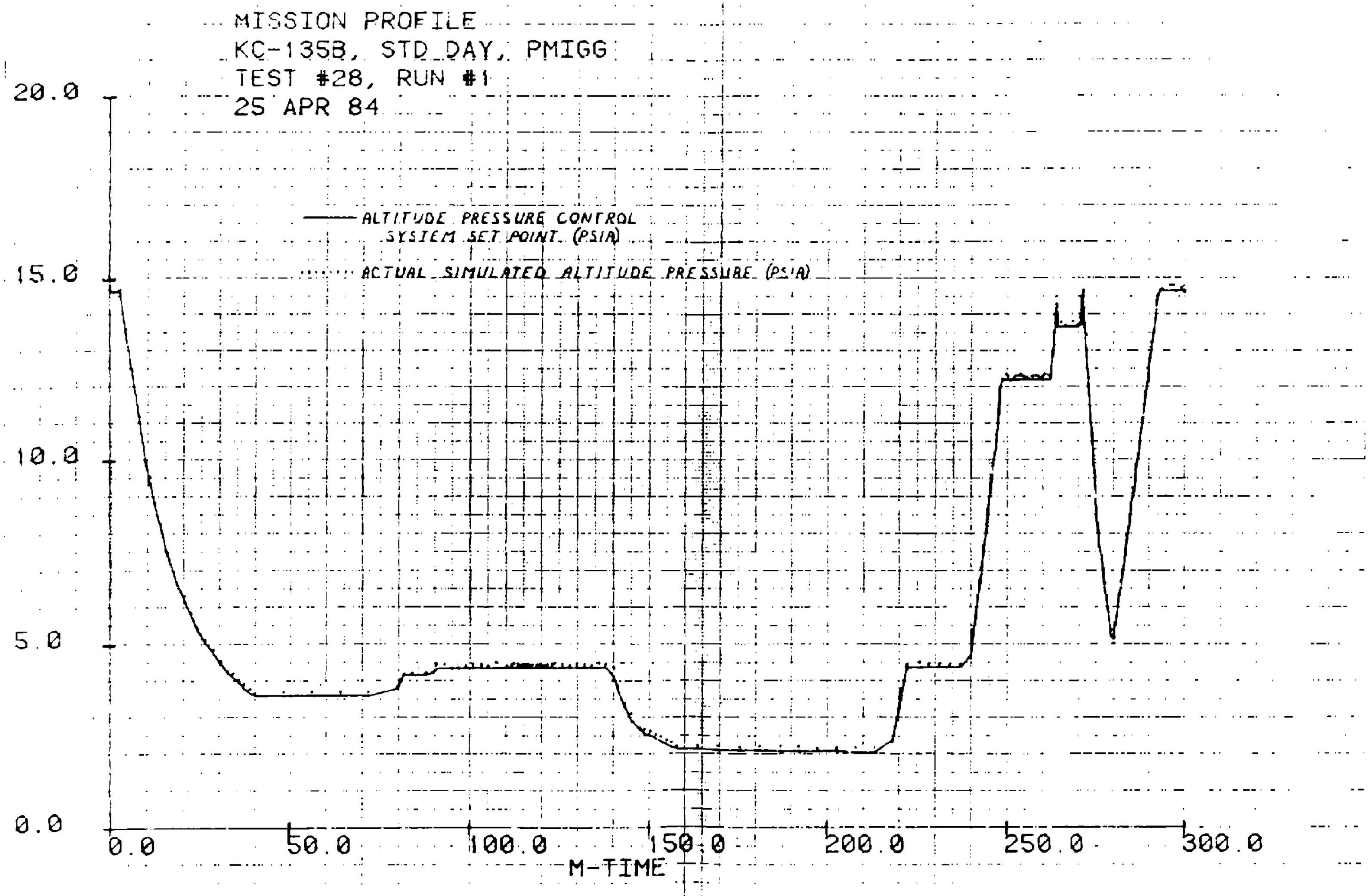

MISSION PROFILE
KC-135B, STD DAY, PMIGG
TEST #28, RUN #1
25 APR 84
ALTITUDE PRESSURE CONTROL SYSTEM SET POINT (PSIA)
ACTUAL SIMULATED ALTITUDE PRESSURE (PSIA)
20.0
15.0
10.0
5.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME

Figure I-13.

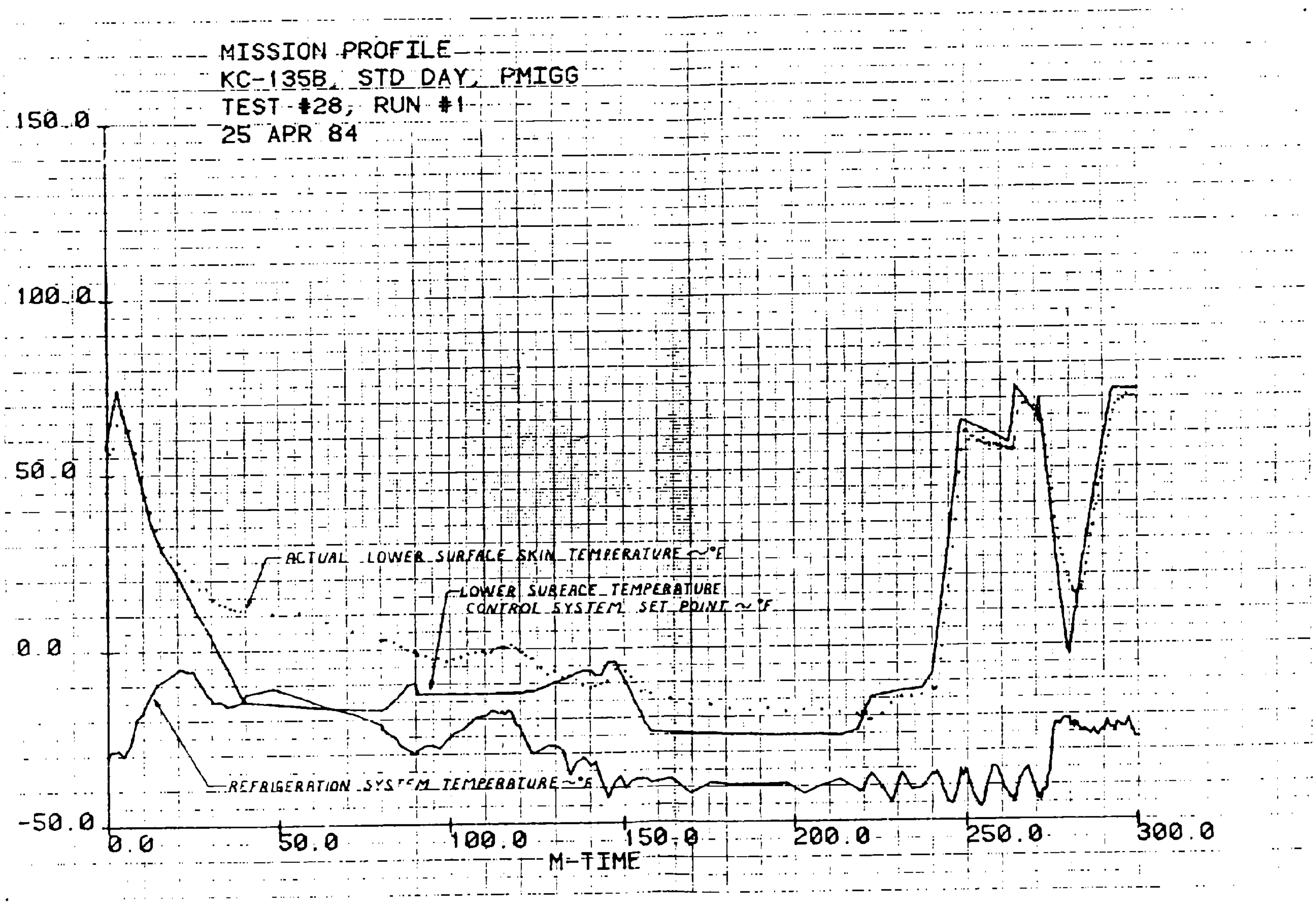

MISSION PROFILE
KC-135B, STD DAY, PMIGG
TEST #28, RUN #1
25 APR 84
150.0
100.0
50.0
0.0
-50.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
ACTUAL LOWER SURFACE SKIN TEMPERATURE ~°F
LOWER SURFACE TEMPERATURE
CONTROL SYSTEM SET POINT ~°F
REFRIGERATION SYSTEM TEMPERATURE ~°F

Figure I-14.

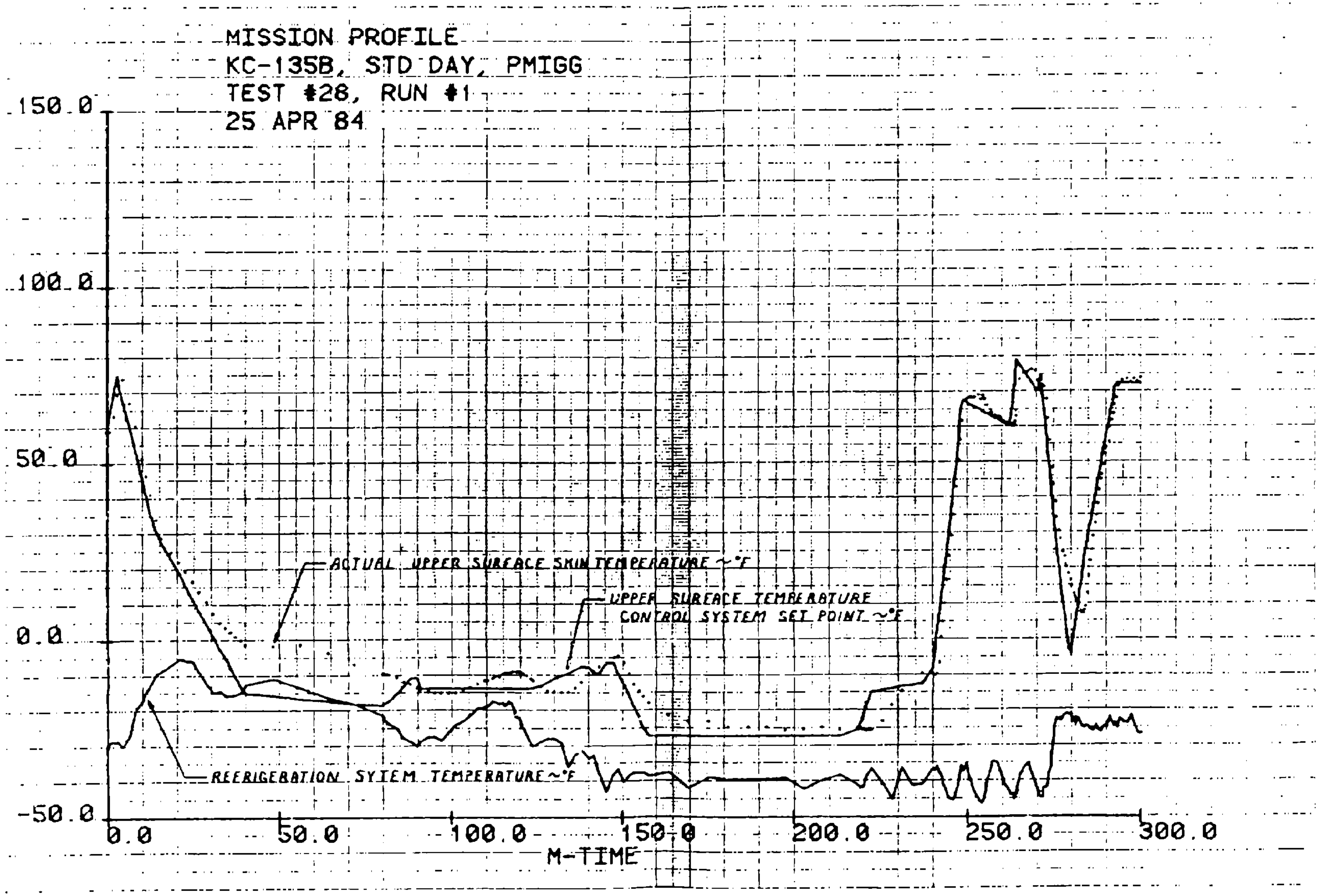

MISSION PROFILE
KC-135B, STD DAY, PMIGG
TEST #28, RUN #1
25 APR 84
150.0
100.0
50.0
0.0
-50.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME
ACTUAL UPPER SURFACE SKIN TEMPERATURE ~°F
UPPER SURFACE TEMPERATURE CONTROL SYSTEM SET POINT ~°F
REFRIGERATION SYTEM TEMPERATURE ~°F

Figure I-15.

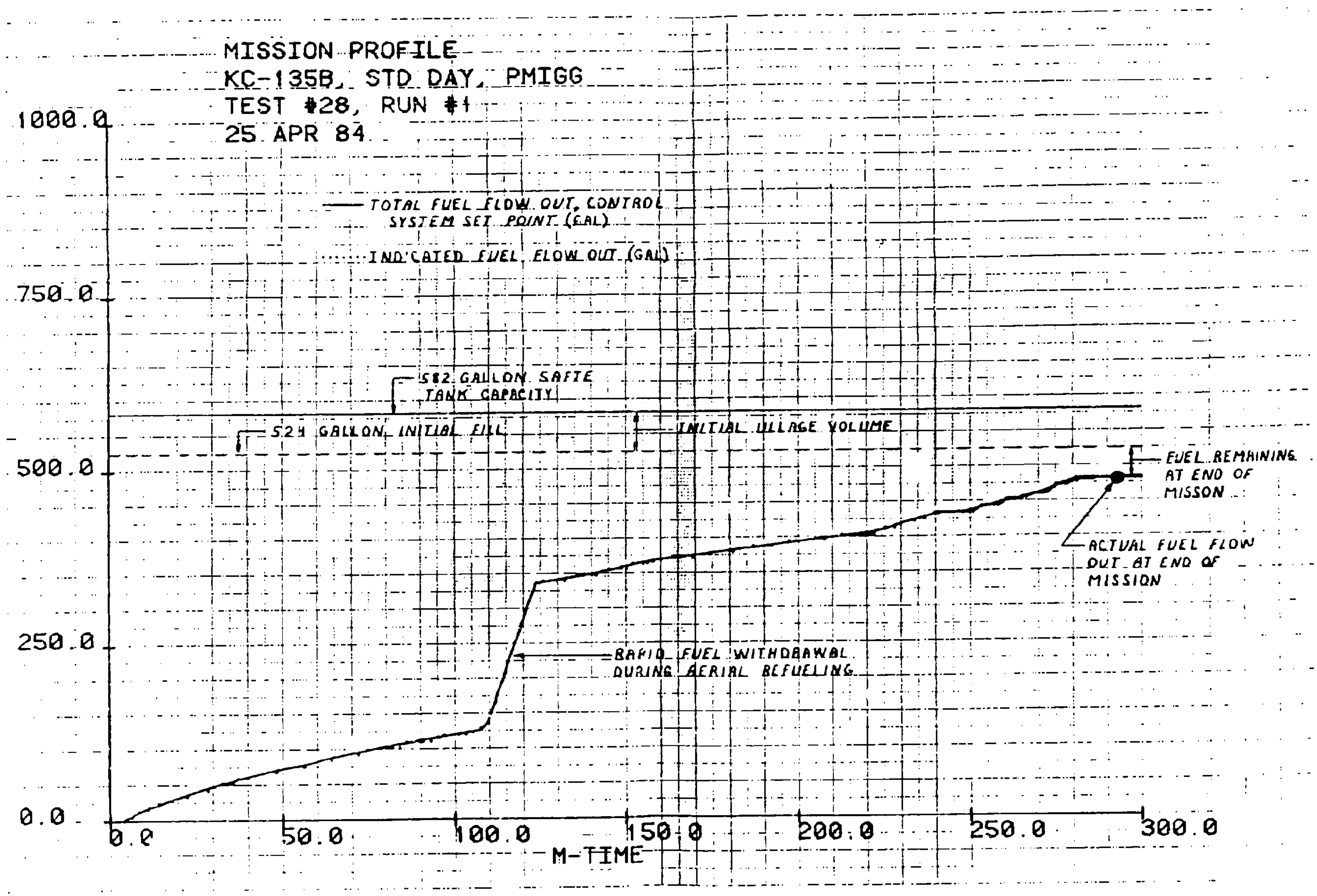

MISSION PROFILE
KC-135B, STD DAY, PMIGG
TEST #28, RUN #1
25 APR 84
TOTAL FUEL FLOW OUT, CONTROL SYSTEM SET POINT (GAL)
INDICATED FUEL FLOW OUT (GAL)
582 GALLON SAFTE TANK CAPACITY
524 GALLON INITIAL FILL
INITIAL ULLAGE VOLUME
FUEL REMAINING AT END OF MISSON
ACTUAL FUEL FLOW OUT AT END OF MISSION
RAPID FUEL WITHDRAWAL DURING AERIAL REFUELING
1000.0
750.0
500.0
250.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
M-TIME

Figure I-16.

APPENDIX J

Repressurization Thermodynamics

The behavior of ullage gas temperature during descents is important when determining the descent requirements for an OBIGGS. AiResearch had predicted (Reference 1) that ullage gas temperature would increase by $120^{o}F$ during the KC-135 descents. Experimental results did not agree with AiResearch's prediction (see Section 5.3 and 5.4).

This disagreement between experimental data and AiResearch's analysis led to a short series of experiments to characterize the thermodynamics of the SAFTE test tank. The experiments were designed to be comparable to the analysis presented in this appendix.

The behavior of a fuel tank ullage during repressurization can essentially be analyzed as a container of gas undergoing a charging process. The assumption of no heat transfer, while greatly simplifying the analysis, yields accurate results only when the process is relatively fast. The thermodynamics of charging a container always cause temperature changes and therefore temperature differences; thus, heat transfer is always involved. For the adiabatic assumption to be accurate, the entire repressurization process must occur before any significant heat transfer can take place.

The analysis of repressurization presented here is based on Reference 9 and is broken down into three parts with matching experimental data. These parts are as follows:

- o Adiabiatic Charging of an Evacuated Container
- o Adiabiatic Charging of a Partially Filled Container
- o Nonadiabatic Charging of a Partially Filled Container

For adiabatic charging of an initially evacuated container from a source of gas having a constant stagnation temperature, the following equation is valid for perfect gas.

$$T_2 = kT_0 \qquad (1)$$

where T_0 = Stagnation Temp of Entering Gas
T_2 = Temp of Gas in Container at Any Time During Charging
k = Ratio of Specific Heats = 1.4 for Air

For the purpose of this analysis, the ullage gas will be considered to be air. Therefore the maximum ullage gas temperature obtainable during any charging process with air would be 1.4 times the absolute stagnation temperature of the charging gas.

If the container is partially filled at the beginning of an adiabatic charging process, and the entering gas temperature equals the initial temperature of gas in the container, the following equation applies:

$$\frac{T_2}{T_1} = \frac{k\left(\frac{P_2}{P_1}\right)}{\left(\frac{P_2}{P_1}\right) + k - 1} \tag{2}$$

where T_1 = T_0 = Initial Gas Temp
T_2 = Final Gas Temp
P_1 = Initial Gas Pressure
P_2 = Final Gas Pressure

The experiments performed with the SAFTE tank could not begin with an essentially evacuated tank since the lowest initial pressure obtainable was 0.5 psia. However, data suitable for direct comparison to Equation (2) was obtained by charging the SAFTE tank from an initial pressure of 0.5 psia to a final pressure of 14.7 psia. These data are presented in Figures J-1 and J-2. Also included in Figure J-1 are data from the adiabatic prediction of Equation (2). Note that experimental data fall well below the adiabatic prediction. Figure J-2 contains data from a relatively fast repressurization (comparable to a descent from 75k ft to S.L. in about 40 seconds) and indicates that ullage gas temperature is still well below adiabatic predictions. In fact, the process would be better described isothermally than adiabatically.

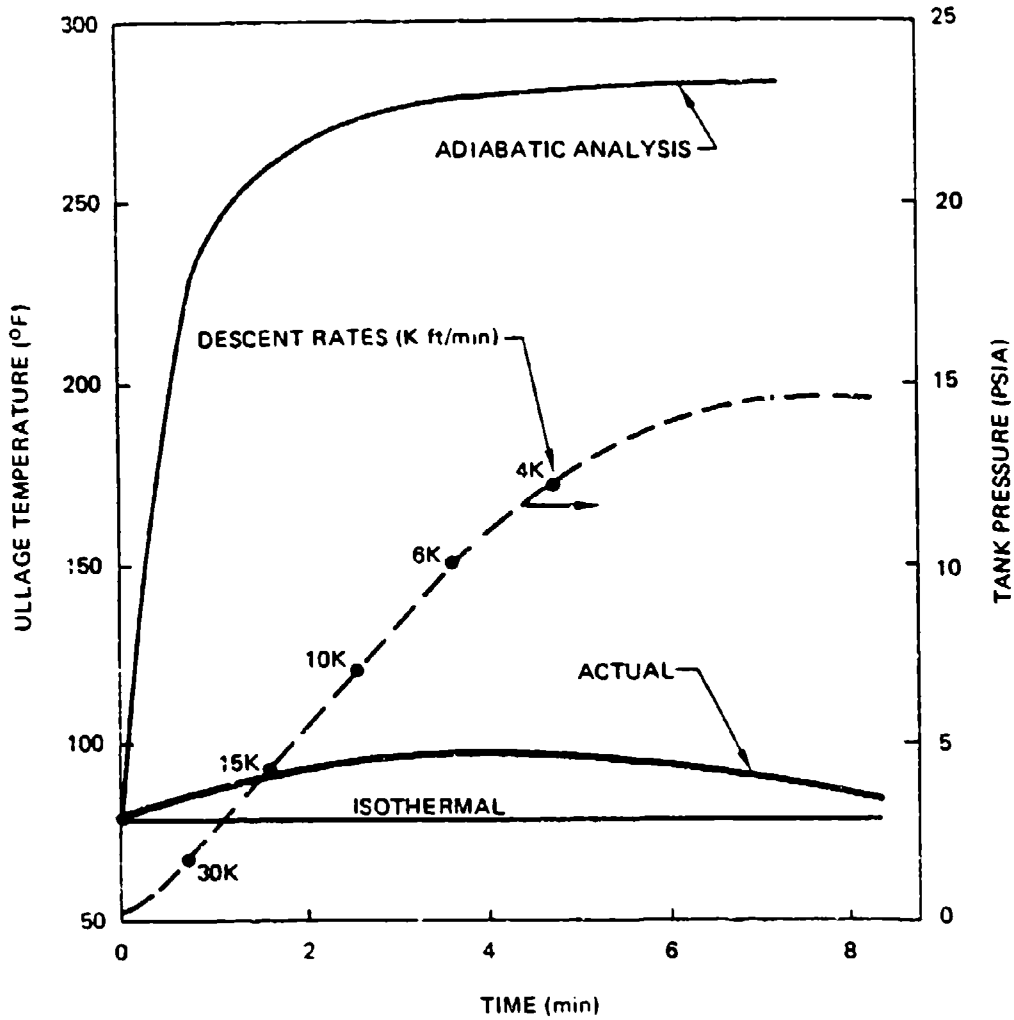


Figure J-1. Ullage Repressurization, Adiabatic Analysis Comparison with Experimental Data

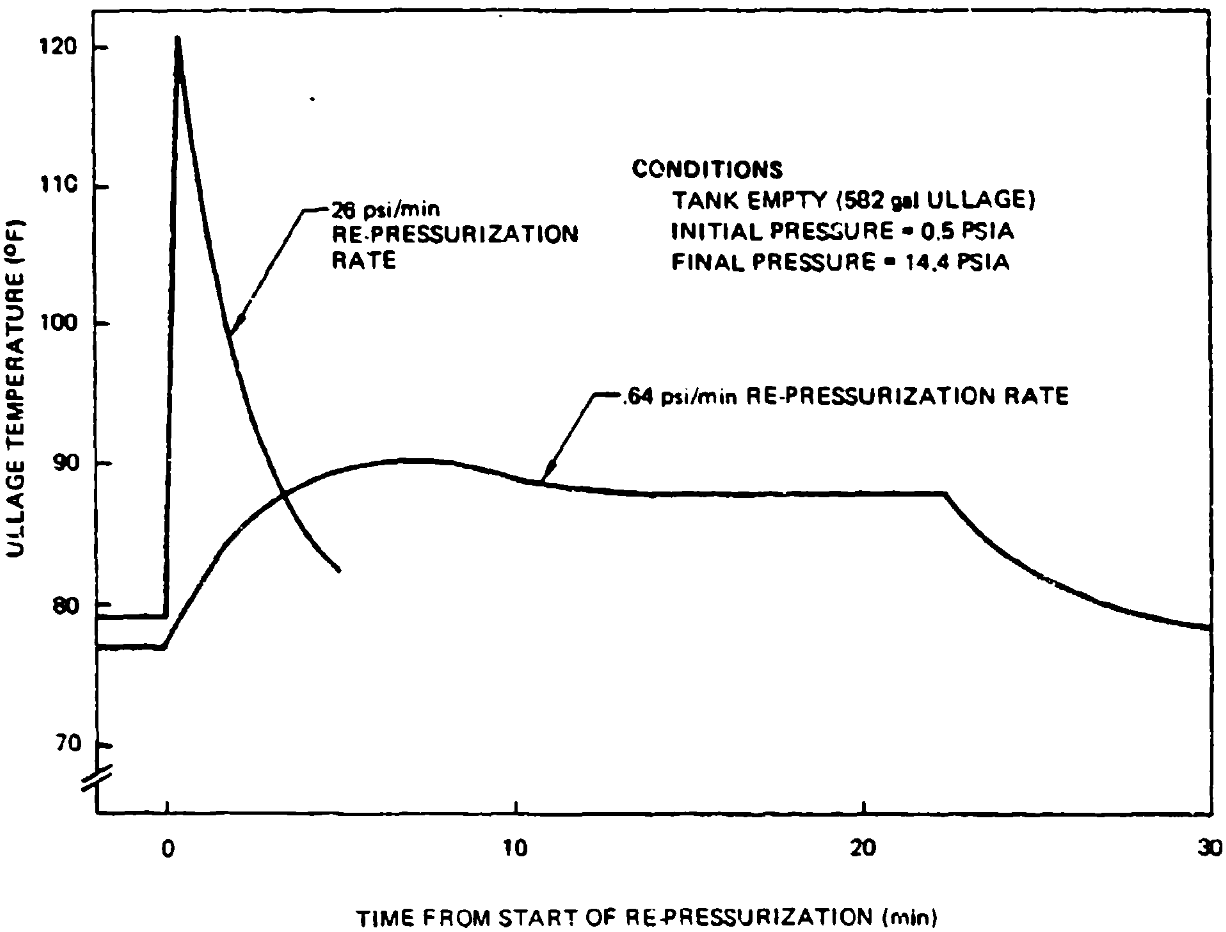


Figure J-2. SAFTE Tank Re-Pressurization Tests

These experimental and analytical data support the conclusion that in an airplane fuel system, the descent repressurization process is approximately isothermal. Taking into account that the wall temperatures will be changing during descents, a more accurate and useful conclusion should be that the ullage temperature will be dominated by the wall temperatures.

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